

2 May

SQT

DRA

# Applications of Aerospace Technology in the Electric Power Industry



(NASA-CR-138947) APPLICATIONS OF AEROSPACE TECHNOLOGY IN THE ELECTRIC POWER INDUSTRY (Denver Research Inst.)  
 416 p HC \$9.00 CACL 10B N74-28537  
 96 G3/03 16895 Unclas

Reproduced by  
**NATIONAL TECHNICAL INFORMATION SERVICE**  
 U.S. Department of Commerce  
 Springfield, VA. 22151

#### ACKNOWLEDGMENTS

This document was prepared for the Technology Utilization Office, National Aeronautics and Space Administration, as part of the Program for Transfer Research and Impact Studies (TRIS) at the Denver Research Institute, Denver, Colorado. This program is directed by Jerome J. Rusnak and Eileen R. Staskin. The principal investigator for this study was F. Douglas Johnson, with assistance from James E. Freeman, Joanne M. Hartley, William M. Hildred and James P. Kottenstette.

Much of the information was gathered with the assistance of NASA in-house and contractor personnel who participated in the development and application of the technology discussed.

The technology reviewed in this document and the applications noted represent the best knowledge available at the time of preparation. Neither the United States Government nor any person acting on behalf of the United States Government assumes any liability resulting from use of the information contained in this document, or warrants that such use will be free from privately owned rights.

APPLICATIONS OF AEROSPACE TECHNOLOGY  
IN THE  
ELECTRIC POWER INDUSTRY

*Prepared for*

The Technology Utilization Office  
(Code KT)  
National Aeronautics and Space Administration

Contract NASW-2362

*Prepared by*

Industrial Economics Division  
Denver Research Institute  
University of Denver

August 1973

## TABLE OF CONTENTS

Section	Page
INTRODUCTION .....	1
I. AN OVERVIEW OF THE ELECTRICAL ENERGY FIELD .....	3
II. SELECTED NASA CONTRIBUTIONS TO THE TECHNOLOGY OF THE ELECTRIC POWER INDUSTRY .....	13
III. DISSEMINATION AND UTILIZATION OF NASA TECHNOLOGY .....	29
IV. PERSPECTIVE .....	35
ATTACHMENT I. The Technology of Electric Power Generation .....	37
ATTACHMENT II. Overview of Lewis Research Center Activity in Electric Power Generation Technology .....	49
ATTACHMENT III. NASA Publications Relevant to the Electric Power Industry .....	55
ATTACHMENT IV. Summaries of Technology Transfer Examples Involving the Use of NASA Technology in the Electric Power Industry .....	61
REFERENCES .....	109

## INTRODUCTION

This review was undertaken to understand further how mission-oriented research and development, such as that performed by the National Aeronautics and Space Administration, supports the continued industrial development that characterizes a modern nation.

The basic premise investigated here is that venturesome, mission-oriented R&D, which culminates in manufactured equipment and apparatus, calls into being fundamental advances in scientific and engineering disciplines; these advances underpin the generic technologies of seemingly unrelated industrial sectors. This document specifically examines the technological commonality between the aerospace and the energy sectors by focusing on selected NASA contributions to science and engineering that are already affecting progress in the electric power industry.

When the electric power industry is compared with the aerospace industry in terms of economic, social, and political dimensions, there is little commonality. However, when these industries are examined in terms of technological dimensions, such as their mutual dependence on improvements in materials science, combustion engineering, and control theory, then important linkages are observed. In this way, the technological gains of one industry directly affect progress in other industries. Since the linkages are obscure and are effected without fanfare, little is known about their pervasiveness. Yet, a better understanding of these linkages provides a more accurate assessment of the value of mission-oriented R&D and, furthermore, facilitates strengthening such linkages.

This document is presented in two major parts. The first part is organized into four sections: an overview of the electric power industry, selected NASA contributions to progress in the industry, linkages affecting the transfer and diffusion of technology, and, finally, a perspective on technology transfer issues.

The second part provides supporting information in the form of attachments: Attachment I provides a description of the major technologies used in the production of electricity; Attachment II reviews the research program of the Lewis Research Center as it particularly relates to the conversion of energy and the production of power; Attachment III provides a list of selected NASA documentation germane to energy conversion technology; and Attachment IV provides further examples of the transfer and diffusion of NASA technology within the electric power industry.

## SECTION I. AN OVERVIEW OF THE ELECTRICAL ENERGY FIELD

Momentary reflection on the nature of the conveniences in a modern home, accompanied by a consideration of what would have been the likely appliances in an average residence twenty or thirty years ago, will vividly convey the tremendous importance of electrical energy for modern living. Appliances in the modern "all electric" home consume an average of 20,000 kilowatt-hours (Kwhr) each year, about three times the average residential consumption and more than five times the average residential consumption of only ten years ago (Federal Power Commission, 1971).

There are many reasons for this impressive growth. The most important ones include the convenience and low cost of electrical energy. Self-defrosting refrigerators, for example, consume considerably more electricity than manually defrosted models; one utility reports the differences at 1,400 Kwhr per year, although part of the difference is attributed to the continuing increase in refrigerator size. In 1972 almost one-third of the 2.1 million new housing units were built with electric heating systems. This percentage is expected to climb rapidly in the years ahead as restrictions on new connections for natural gas limit builders' choices to electricity or fuel oil (Olmsted, 1972).

While the average price of residential electricity rose to 2.3 cents per Kwhr in 1972, the decade of the 1960's saw the cost of electricity decrease almost 10 percent. The recent increase in cost primarily reflects the effects of increased fuel costs and expenditures for pollution control equipment. The fuel economy of base-load nuclear generation is expected to check the recent rise in rates by 1974 and reestablish the long-term downward trend that has traditionally reflected the low incremental cost of supplying increased usage. Thus, in 1972 dollars, the average price per residential Kwhr is expected to drop to 2.01 cents by 1980 and to 1.60 cents by 1990 (Olmsted, 1972).

Total customers served by the U. S. electric utility industry climbed to nearly 76 million during 1972, with residential customers comprising 92 percent of the total. However, industry is the largest consumer of electrical energy, as shown in Figure 1-1.

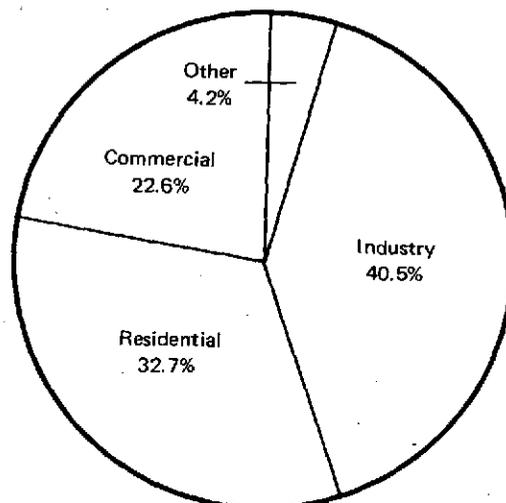


Figure 1-1. Electrical Utility Sales in 1972, by Consumer Class, for 1,595 Billion Kwhr. [Source: Olmsted, 1972.]

Industrial use is exemplified by the production of primary metals: each ton of raw steel requires 400 Kwhr, and induction heating of the steel for hot rolling requires more than 300 Kwhr (McElheny, 1971). In 1970 the primary metals industry used as much electricity as 18 million average residences (U. S. Department of Commerce, 1972).

To meet this demand for electrical energy, generating capacity grew by 37,000 megawatts (Mw), almost 10 percent during 1972. While this growth shattered all previous records for additions in a calendar year, the record will be short lived as forecasts for annual additions in generating capacity show a steady increase to an expected 72,000 Mw in the year 1990 (Olmsted, 1972).

In recent years, the investment in new generating capacity has increased to more than 55 percent of the total annual capital expenditures made by the electric utilities. In 1972 these expenditures exceeded \$16 billion, over four times the 1962 expenditures. Once again, this growth rate is expected to continue at a rapid pace, as shown in Figure 1-2.

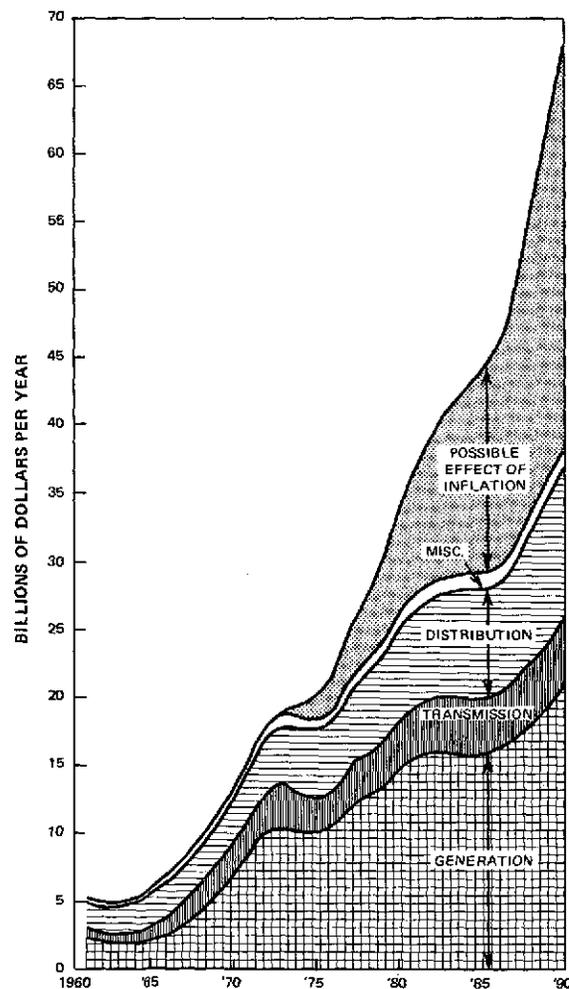


Figure 1-2. Capital Expenditures by Electric Utilities. [Source: Olmsted, 1972.]

### Electricity and the Total Energy Picture

The problems of electric utilities are an important part of the quandary posed by total energy consumption in this country today. Electricity is just one form of energy derived from a variety of resources such as coal, oil, gas, uranium and water. In 1970 Americans used the equivalent of more than 2 trillion Kwhr, about 35 percent of all the energy used in the world that year. Transportation and electricity generation each required a fourth of the total energy expended, and direct heating accounted for another 40 percent (White, 1971). Nearly all of this energy was derived from fossil fuels—as shown in Figure 1-3. Hydropower provided less than four percent and nuclear energy only 0.3 percent (Starr, 1971). Minute amounts of energy came from geothermal sources in the United States.

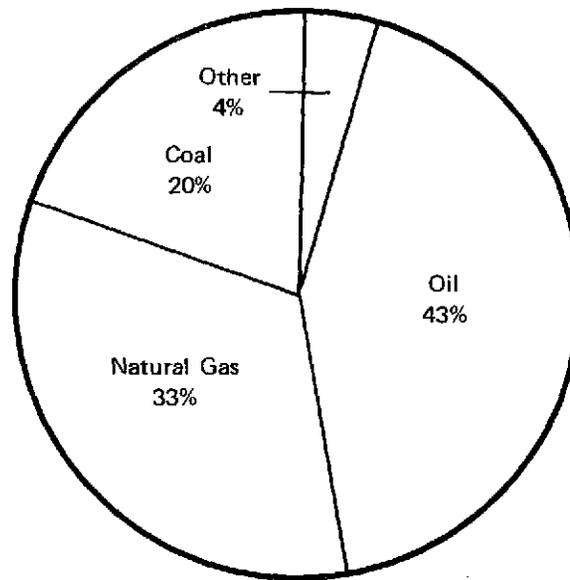


Figure 1-3. Sources of Energy Used in the United States During 1970. [Source: Starr, 1971.]

Historically, economic growth has been associated with energy use. It has been estimated that a primitive man probably used only about 2 Kwhr per day, resulting mainly from his food consumption. Domestication of fire boosted his energy use to about 4 Kwhr per day, and domestication of animals allowed an increase to nearly 14 Kwhr. The early industrial advances that occurred after 1850 raised daily per capita use to 80 Kwhr, and the advances of this century called for a daily use in 1970 of 268 Kwhr per American (Cook, 1971). International comparisons of energy use associated with GNP suggest the same conclusion (see Figure 1-4).

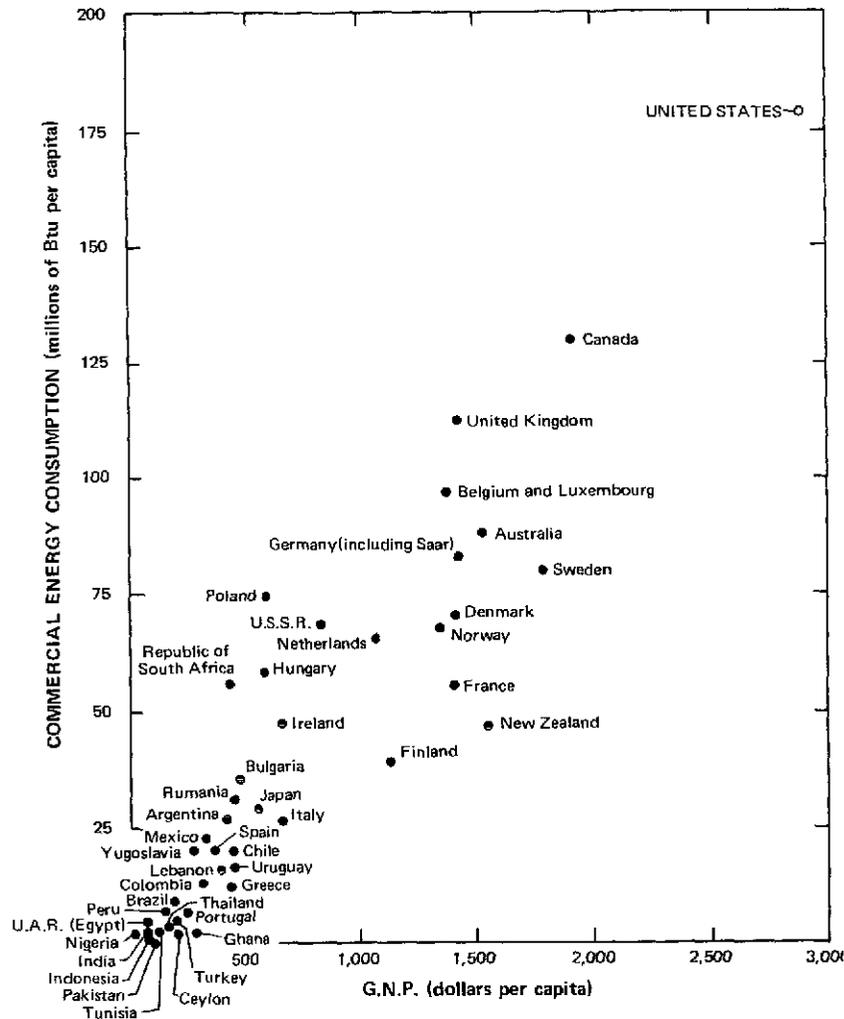


Figure 1-4. Per Capita Energy Use and Per Capita Gross National Product, Selected Countries, 1961. [Source: Energy Study Group, 1964.]

Many commentators are now discussing the “energy crisis.” As the use of energy has increased in recent decades, the economy has become more productive; but as energy use-rates continued to increase each year, a whole series of new problems arose. The annual growth rate of energy use in this country has been about three percent compounded for almost one hundred years. The rate was low from 1880 to 1930—about 1.2 percent per year; it increased to 2 percent during the 1930-1960 period and to 2.7 percent between 1960-1970. The rate from 1965 to 1970 was higher yet—4.9 percent.

Not only is the rate of growth of energy use rising on a compound growth curve, but shifts in the composition of energy supply are occurring in a manner that magnifies the growth strains: electricity use has been rising at nine percent each year as more applications are found for electric power and as more people are added to a population which uses electricity (White, 1971). Figure 1-5 illustrates this trend toward an “all electric” economy.

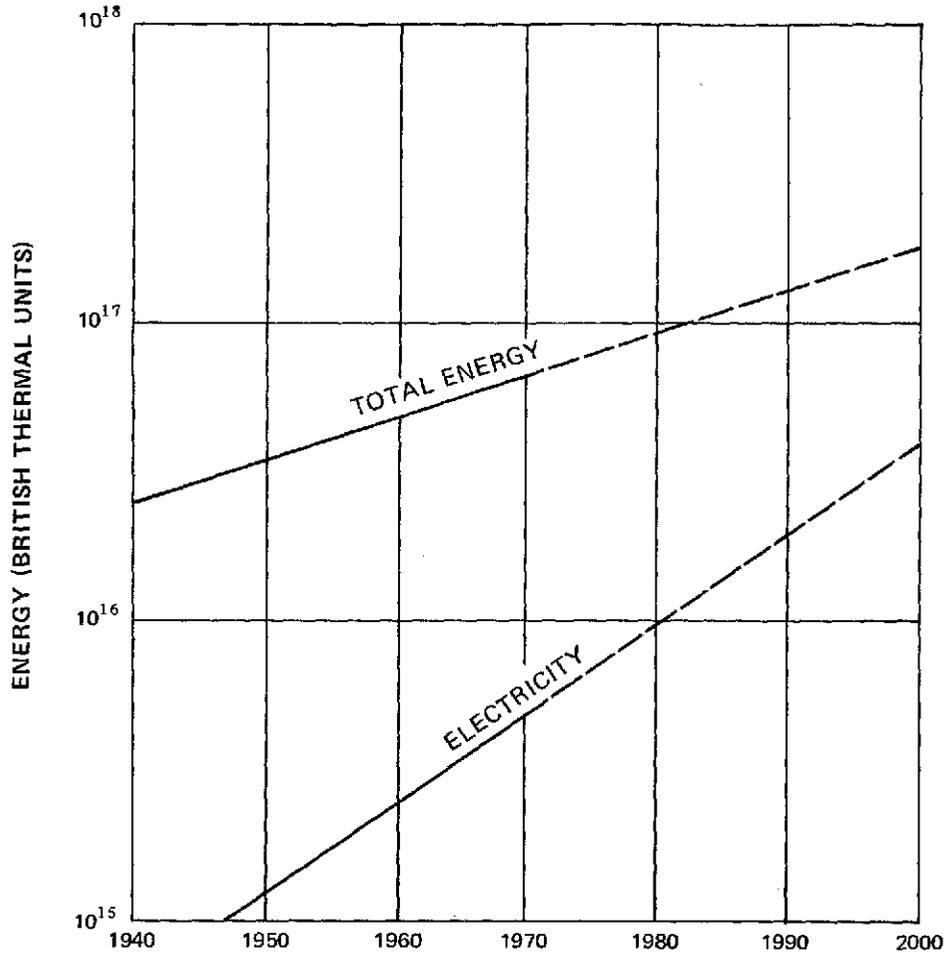


Figure 1-5. Energy Projections.\* [Source: Gregory, 1973.]

The most widely discussed problems of energy supply relate to resource depletion. An exponential increase has occurred in the rate of exploitation or depletion of known energy sources. For example, the amount of coal produced and used since 1940 is about the same as the total consumption of coal in all times prior to 1940. Of the cumulative (to 1970) production and use of petroleum of 227 billion barrels, half of the activity occurred between 1959 and 1969 (Hubbert, 1971).

Such exponential rates of increase obviously cannot continue indefinitely, since the total resources, while unknown, are finite. Thus a widespread concern for future supplies of energy resources is evident. Estimates of available fossil fuels vary, but there is general agreement that known fossil energy sources and technology cannot sustain the foundation for the kind of economic growth that the United States has experienced in this century. The mathematics of compound growth and doubling periods makes this

---

\*Accelerating trend toward an "all electric" economy is evident in this graph, which shows that the demand for electricity (bottom line) is growing in the U. S. at a much higher rate than the overall energy demand (top line). Assuming that the trend continues, the U. S. is heading for a predominantly electrical economy sometime in the 21st century. The data are from the U. S. Department of Commerce and the Edison Electric Institute.

clear. The use of energy is doubling about every 14 years and that of electricity is doubling in less than 10 years.

The necessity of new technology is evident from any consideration of the relatively short time within which exhaustion of known reserves of commonly used clean energy sources, deliverable with today's technology and at today's prices, will occur. Without new technology, and perhaps even with it, price increases may become quite burdensome. The U. S., for example, possesses an abundance of energy resources which include identified but submarginal deposits that cannot be recovered economically at current rates. With progressively improving technology, these resources could become developed on a large scale (Jones, 1973).

Though new technology may ultimately mitigate the effects of resource depletion, present energy conversion technologies must be used until that time, and this necessarily involves the question of environmental impact. Environmental problems demand both new conversion methods and major modifications of the standard methods. New technologies are appearing which advance the ability to monitor and control these problems, but to some observers, the longer-range and more serious problems of both fossil and nuclear fuels relate to production of waste heat. C. M. Summers, for example, concludes that waste heat production is the ultimate constraint on any energy system and that perpetual increases in waste heat generation are ultimately inconsistent with life on this planet. He calls for extensive research to find "invariant" energy systems that do not add to the heat load of the biosphere (Summers, 1971).

Utility managers may find such considerations a distraction as they try to cope with the more immediate problems of rising fuel costs, installing pollution abatement equipment, acquiring land sites, and rising construction costs and interest rates. It is clear, though, that new decision-making processes are emerging within a framework that will require managers to consider factors which, up to now, they have taken as extraneous. Licensing delays, siting delays, and imposition of environmental constraints are in their infancy. These issues have been politicized, and their resolution will increasingly be in legislative and judicial proceedings. The outcome for the decision-making process is likely to be more far-reaching than the analogous results of labor legislation of the 1930's. Those legal changes permanently altered the decision-making process: unilateral decisions by management were displaced in favor of collective bargaining, and the list of negotiable items has grown each year.

These reflections suggest that the problems of energy supply include a mix of the political, social and economic factors. However, it remains clear that technological dimensions will continue to be crucial, if only to provide options and maneuverability within the social-economic-political milieu. Thermal efficiency, waste heat, transmission losses, and the like will be problems regardless of the trends of fuel prices, interest rates or political constraints. Only the existence of options regarding the technological problems will provide workable solutions within the system of constraints. The main focus of this review, therefore, is on the technological characteristics and research and development problems of the electric power industry, particularly in the area of energy conversion. Attachment I presents a commentary on the present state of energy conversion technologies.

### **The Need for R&D**

Rapidly rising demands for electricity, compounded by scarcity of clean fossil fuels, delays in installing nuclear capacity, environmental constraints, and other factors, have clearly placed utilities in a difficult position. It seems obvious that a major component of management concern in the electric

power industry should be development of a wide variety of new technologies, both incremental for the short term and stepwise for the long term. Brownouts and voltage reductions are evidence that the situation of the industry is at least locally fragile. A necessary, if not sufficient, condition for finding solutions to energy problems is the availability of many technological options, which means that R&D activities on a broad front are necessary.

From the perspective of economic analysis, R&D—especially for basic research—is inadequately funded when left exclusively to private sources. According to a study done by the National Science Foundation, the return on R&D investment is just about equal to the return on invested capital. This fact helps explain why private industry chronically underinvests in R&D. And, according to the Council of Economic Advisors, if market forces are allowed to determine the level of R&D investment, this underinvestment will continue (Khol, 1973).

This phenomenon has also been noted universally by economists (see, for example, Arrow, 1962, Nelson, 1959, and Foster-Pegg, 1966). One reason for this situation is the existence of external effects: the originator of a new technology captures only a part of the gain from its use, with other firms and society in general capturing the rest of the gain. The innovator is consequently motivated to spend less for R&D than if he could internalize the entire gain. If his spending is deficient, social benefit is lost. Furthermore, basic research typically has a long gestation time and is expensive and risky; the private sector thus finds it difficult to justify spending scarce funds for this kind of research.

Historically, direct expenditures for R&D by utilities have been low—an average in 1970 of 0.25 percent of gross revenues and a median of 0.03 percent of gross revenues (Barrett, 1972). By way of comparison, manufacturing industries spent an average of 1.5 percent of sales on R&D in 1970 (U. S. Department of Commerce, *Statistical Abstract of the United States: 1972*). Such figures do not reflect the fact that the electric power industry has relied heavily on manufacturers to do R&D and pass along the costs in the price of purchased equipment. While this has led to important advances, it is not an altogether satisfactory arrangement, because it does not provide for comprehensive systems-oriented technology.

The linkages among the utilities, equipment manufacturers, and primary metal producers are such that each is concerned with different kinds of technological advance, and one industry's product improvement is another's process improvement. In general, a firm can be expected to pursue process improvements to reduce its costs; it will seek product improvements in order to obtain a greater share of the market. Spending for either kind of improvement is conditioned by the ability to internalize the resultant gains. Where gains accrue primarily to others, there will be little interest in making improvements. This ability varies within the chain, from utilities back to primary metal producers and fabricators, and can be elaborated as follows:

- Opportunities for product improvement at the level of the utility company are minimal. Electricity is a standardized product, not easily altered with respect to its salient characteristics. The user wants an adequate supply of electricity at a standard voltage and frequency. R&D for product improvement is thus related to delivery systems almost exclusively. Delivery of the desired commodity is a function of the utility's *process* technology, and improvements in this technology are largely embodied in the *products* of equipment suppliers.

Since the utility company is a local monopoly, it has less incentive to conduct R&D than if it were confronted by a more competitive environment. Competitive pressure from alternate energy sources is not sufficient to call forth a socially optimal level of R&D. If technological advances were shared by other utilities, their adoption would increase the total social gain; however, the original innovating utility would not capture any of the financial reward. Heretofore, there has been little reason to expect individual utilities, each funding R&D at a level consistent with a return each can internalize, to conduct R&D at a socially optimal level. This situation does, however, help clarify a major reason for the utilities' reliance on equipment suppliers as sources of technological improvements.

- In contrast to the utilities, individual equipment manufacturers can largely internalize the results of R&D, which improves their proprietary products and process technologies. Their market shares can be increased by providing products at lower cost or with superior performance capabilities. Therefore, these firms are motivated to fund R&D for improving both their production technologies and product attributes. Still, this situation seldom produces a socially optimal level of R&D for electric power because of the high risk and low return on R&D investment.

The specific and perhaps unique requirements of an individual utility may call for considerable custom design work, the results of which do not apply generally to other equipment for other customers (Humphries and Guild, 1971). Where this is the case, the supplier has less incentive to fund R&D above the level that allows completion of the particular job, a level lower than if the problem solution were widely applicable.

- Finally, some problems that affect the efficiency of utilities' operation have their sources in materials technology. In these cases, electrical equipment manufacturers must rely on the primary metals industries to improve their products, and this introduces the possibility of still another short-fall from an optimum level of electric power R&D spending. Primary manufacturers will necessarily limit their R&D activity that applies to a specific segment of their total market.

#### **Institutional Changes in the Electric Power Industry**

Taken together, these structural traits of the electric power industry and its suppliers have called into being new institutions and activities to increase R&D for electric power. The Electric Research Council, the predecessor of the Electric Power Research Institute (EPRI), was one such institution. Organized in the spring of 1965, the Council sought to provide a means by which the various segments of the electric utility industry could join in cooperatively supporting research of industry-wide importance.

In the fall of 1969, the Electric Research Council appointed its Research and Development Goals Task Force to establish R&D goals together with priorities and cost estimates. The specific goals identified for research and development related to energy conversion are enumerated in Table 1-1.

TABLE 1-1. R&amp;D GOALS FOR ENERGY CONVERSION\*

- 
1. Establish Nuclear Breeder Reactors as being commercially available for purchase by the mid-1980's for central station baseload applications.
  2. Improve present methods of generation in efficiency, reliability and environmental impact. Continue development of gas turbine-steam combined cycle.
  3. Establish scientific feasibility of Nuclear Fusion within five to eight years and make it commercially available for purchase by the mid-1990's for central station baseload applications.
  4. Establish gasified coal fuel as economically available for gas turbines, MHD, and conventional boilers by 1975. Continue research on other methods of fuel preparation such as hydrogen production and solvent processing.
  5. Establish open cycle MHD as being commercially available for purchase by the mid-1980's, using gas, oil, coal, or coal derived fuel, for central station baseload applications topping either steam or gas turbines. Establish the MHD portion of these combined cycle plants for peaking and emergency power requirements.
  6. Establish Fuel Cells in the 10- to 20-Mw size range as being commercially available for purchase by the late 1970's for substation application, fueled by natural gas, hydrogen, or fuels derived from coal or oil.
  7. Continue research on high energy bulk storage batteries for peaking purposes.
  8. Continue R&D for unconventional cycles such as potassium-steam binary cycle and Feher CO<sub>2</sub> cycle. Continue research on thermionics for topping nuclear and fossil generating plants.
  9. Proceed with additional research on solar energy at a moderate funding level.
  10. Continue basic research for new methods of energy conversion.
- 

\*Source: Electric Research Council, 1971.

Subsequently, the Electric Research Council worked out the details of an industry-wide organization that would be able to provide direction and support for such a program. As a result, the Electric Power Research Institute was established in March 1972, absorbing the Electric Research Council, its R&D programs, and those of the Edison Electric Institute.

The EPRI, headed by Chauncey Starr, was formed by investor, government, and publicly owned utilities to carry out cooperative research for conversion, the improvement of conventional methods of generation, transmission and distribution, and the development of new technology for the utility

industry. The analysis, planning, and management functions of EPRI will be carried out by an in-house professional staff of 100 to 200 individuals.

EPRI is sponsored by almost all electric utilities on a voluntary funding basis. The present funding formula is equivalent to a starting level of roughly 0.5 percent of the cost of electricity to the consumer and will rise to a level of about 1.0 percent in the next years. At present, over \$60 million has been pledged for 1973 and \$96 million for 1974. Of the total budget, about 20 percent may be retained by the individual utilities to be used on local research (Starr, 1973). The formation of EPRI is intended to address the problem of internalizing costs and benefits of research for the individual utility. It is hoped that with this allocation of support funds, EPRI will not only be able to provide unified and long-range national energy planning but also will focus upon unique and short-term problem areas of regional importance.

While utilities are increasing their R&D outlays to share the costs of the broad range of research needed for stepwise advances, there is an obvious case for more government-funded basic research in the area, if only to realize the gains that may be lost because of externalities.

Dr. Chauncey Starr has suggested, for example, that the federal government should bear the major burden for exploratory research such as that related to the fusion process (Starr, 1973). Such government intervention has already begun. Several bills related to power R&D are being considered by Congress, and the National Science Foundation recently formed a task force to study plans for energy-related R&D in support of the program presented in the President's Energy Message to Congress.

### **Conclusion**

The problems facing the electric power industry are indeed mindboggling. The galloping demand for electrical energy must be accurately predicted long before new systems go on-line. It is not surprising, then, to see industry leaders often focusing their attention on the long term when they consider R&D programs.

Yet, today's demand for adequate and reliable power continues to be the major concern of managers in the electric power industry. In this regard it is crucial that existing, applicable technology which has resulted from government-funded R&D be utilized, both to increase the return from the public investment already made and to avoid duplication of expensive research that has produced usable results.

This study, therefore, concentrates on this second concern by exploring a number of technological advances coming from NASA R&D that have already contributed to the technological base of the electric power industry. While the future may witness earthbound adaptations of systems developed to provide power for space missions, advances in generic technologies are already being applied.

## SECTION II. SELECTED NASA CONTRIBUTIONS TO THE TECHNOLOGY OF THE ELECTRIC POWER INDUSTRY

The evolution of equipment in the electric power industry has called into being advances in technological disciplines across a broad front. These advances have contributed to the body of technical knowledge that underpins many industries; and, likewise, the electric power industry has benefited from advances in other industrial sectors. Secondary utilization of a technological innovation requires both the perception of its relevance and its adaptation for specific new applications. The description in this section focuses on the relevance and adaptation for selected NASA innovations in materials science, combustion, and process control to the electric power industry.

Attachments II, III, and IV extend the presentation in this section: a survey of the comprehensive program for energy conversion and rotating equipment at the Lewis Research Center in Cleveland, Ohio (Attachment II); an illustrative list of titles for NASA technical publications arranged by technical discipline (Attachment III); and the description of more than 60 examples of technology transfer from NASA to the electric power industry (Attachment IV). These attachments indicate that the examples cited in this study are not isolated cases and that the utilization of NASA technology by the electric power industry will increase.

### Material Science

Every engineer—mechanical, civil, electrical, nuclear or other—is vitally concerned with the materials available to him. Whether the product is a bridge, a computer, a space vehicle, or a gas turbine, the engineer must have an intimate knowledge of the properties and behavior of the materials he plans to use. This information must be specified for the oftentimes harsh environment experienced by the end product. For steel alone, there are over 2,000 different alloys available (Van Vlack, 1964). It is easy to see, then, how the engineer is confronted by a myriad of alternatives when it comes to designing new products.

Most often, designers rely on past experience for answers to many of the questions they face. The needs of society, however, continually demand innovative design approaches that push the limits of knowledge about material behavior. In the electric power industry, for example, the largest General Electric steam turbine in service by 1951 was a cross-compound unit rated at just above 200 megawatts; by 1964, GE had 650-megawatt units in service (Young, 1964). And today even larger units—1,000 megawatts and above—are operating. Tandem units have similarly increased in size, and units of about 900 Mw are operating.

This increased capacity cannot be achieved simply by making units bigger. Higher temperatures, higher pressures, and greater stress are also an important part of this increased capacity. Furthermore, as components, products, and systems become larger, they must also become more reliable because there is a greater dependency upon them. The first stage of a modern turbine-generator by itself can produce over 200 megawatts of power—as much as an entire turbine-generator in service in 1950 (Young, 1964). The inference here is simple—as generating equipment becomes larger and more complex, there is less tolerance for failure. Not only are power outages inconvenient to users, but they also are extremely expensive for producers.

One of the main causes of forced outages for steam turbines is design deficiencies. In 1970, General Electric reported that 41 percent of the total forced outage hours of large steam turbines was in

some way related to turbine design (Downs, 1970). Half of these failures—20 percent of the total—resulted from components that were larger and/or working harder than other units previously designed. Most often, these components could not be tested in the laboratory under simulated service conditions.

When electric power generating equipment is designed for 40 years of service, repeated failure can be disastrous. In circumstances like these it becomes crucial for designers to know as much as possible about the material they specify. In this regard, then, two important technologies concerned with a better prediction of material performance under load will be examined. These two technologies—fracture mechanics and high temperature material behavior—have been an important part of NASA's research over the last fifteen years.

**Fracture mechanics.** The emergence and rapid acceptance of fracture mechanics during the past two decades grew out of attempts to deal with the phenomenon of brittle fracture. NASA's concern for minimizing the weight of flight systems led to the use of high-strength materials and, ultimately, to new ways of dealing with the problem of brittle fracture of these materials.

Although brittle fracture is most often associated with high-strength materials, several factors can cause a normally ductile material to fail in a brittle manner. One of the most important of these factors is thickness (see Figure 2-1). Thick sections, as commonly used in the construction of turbine rotors, for example, may fail in a brittle manner because of the resistance offered to local yielding. Between 1953 and 1956, GE found that the rotors in several large steam turbine-generator units fractured suddenly and unexpectedly at normal design operating conditions. These rotors had body diameters ranging from three to six feet and lengths up to twenty feet. Detailed investigation revealed that the rotor failures were classic examples of brittle failure, namely, all fractures were initiated at crack-like flaws in the parts. As a consequence, GE initiated a continuing development effort to understand more fully the reasons for fracture and to develop design criteria to prevent future occurrences.

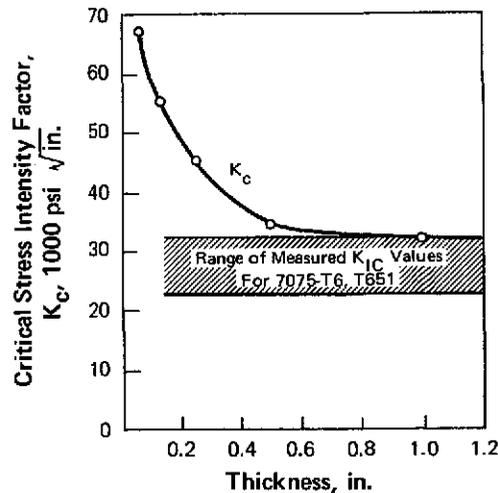


Figure 2-1. Fracture Toughness of 7075-T6, T651 Sheet and Plate From Tests of Fatigue-Cracked Center-Notched Specimens (Transverse). [Source: Kaufman, 1970.]

The problem embodied here is simply that the conventional ductility measurements deal with the gross characteristics of a material, while failure of a structure often is the result of local characteristics such as flaws which grow to a critical size during service life. Such flaws have become the essential consideration in the design of critical power generating equipment. In these instances where high performance materials are used, fracture toughness (resistance to crack propagation), rather than ductility, is the crucial parameter, and the behavior of materials can only be described through the concepts of fracture mechanics.

For years, engineers struggled to make the laboratory measurement of metal fracture properties more than just a subject of research interest. What they lacked was a way to quantitatively relate the theoretical concepts to practical structural analysis. Almost without exception, the analysis of a structural failure reflected the need for a quantitative method to measure the fracture toughness of the materials involved. In this context, development of a plane strain fracture toughness test by engineers at the NASA Lewis Research Center was a major accomplishment. For the first time, a designer could, under appropriate circumstances, directly relate flaw size and growth to load-carrying capability, thereby specifying the service life of structures.

In the electric power industry many products involve heavy section machinery and structures that are made of low-to-intermediate strength steels, such as thick-walled pressure vessels, large forgings for turbine and generator rotors and disks, thick wall castings and heavy welded frames.

Due to the high potential now offered by the linear-elastic fracture mechanics technology for making quantitative engineering decisions concerning fracture prevention, large-scale investigations have been conducted to develop and apply the technology to the design of power generating equipment (Wessel, 1970). The plane strain fracture toughness value ( $K_{IC}$ ), as determined by the NASA-developed test, is fundamental to any linear-elastic fracture mechanics analysis.

Westinghouse Electric Corporation, a major manufacturer of power generating equipment, ran an extensive program to determine fracture toughness ( $K_{IC}$ ) and crack growth data for the three basic alloys used in all large turbine-generator rotor and disc forgings manufactured in the United States. This information continues to be used by designers, materials engineers, and inspection personnel working cooperatively to establish step-by-step fracture prevention procedures for power generating equipment (Greenberg, 1969).

Now that a material's  $K_{IC}$  value can be determined, it is possible to compute critical combinations of load and flaw size using equations for the stress intensity factor ( $K_I$ ). Such equations have been derived for a number of conditions encountered in the design of engineered structures. Lehigh University, building upon work initiated by the National Science Foundation and the Boeing Company, received a NASA grant to develop a thorough compilation of stress intensity factors for flaws likely to be encountered in engineered structures (Paris and Sih, 1965). The  $K_I$  values from this research have been widely used in the design of power generating equipment. For example, the General Electric Company used these stress intensity factors for the geometry of a rotor bore to establish design criteria for rotating equipment (Yukawa, 1969).

While numerous other examples of the use of NASA contributions to fracture mechanics could be cited, an even more fundamental change encompassing these activities is underway. The plane strain fracture toughness test has been institutionalized by both the American Society for Testing and

Materials and the American Society of Mechanical Engineers (ASME). In 1972, after several years of evaluation, the NASA-developed test became part of the ASTM Standards (ASTM Method E 399-72). The ASME Boiler and Pressure Vessel Code has adopted a method for "Protection Against Nonductile Failure" that correlates  $K_{IC}$  values with traditional ductility measurements. Another measure of the effectiveness of fracture studies is reflected in the metal industry's development of new alloys for optimum fracture toughness characteristics (Kaufman, 1971).

**Material's behavior at high temperature.** Interest in the subject of the high temperature behavior of materials is far from being only space-related. Information generated on this subject is applied in many areas of advanced technology, including aircraft gas turbines, diesel engines, steam turbines, nuclear reactors, and land-based gas turbines. In each of these cases the objective is to provide safe operation and reliable performance with a minimum of downtime and cost of repair.

Fatigue, a major cause of failure, is encountered in these applications in several ways. Vibration induced by fluid motion or by rotation can cause failure after millions of small amplitude stress cycles. Another source of fatigue is the thermal cycling introduced by recurring start and stop operations. During rapid heating and cooling, temperature gradients develop, thus producing differential thermal expansion which strains the material nearest the surface. This type of fatigue is identified as thermal fatigue and often results in failure after only a few hundred or thousand duty cycles. The same high strains applied at low temperatures might be absorbed elastically, but at high temperatures, lower strength forces some of the strain to be inelastic. Inelastic straining leads directly to low-cycle fatigue. Additional high temperature effects include: creep-induced intergranular cracking that greatly hastens fatigue crack initiation, accelerated crack growth due to surface reactions with gaseous or liquid environments, aging and phase instability effects that lead to changes in material properties, and local areas of high stress due to applied loads. To complicate matters, all these phenomena can occur alone or simultaneously while a part is in service.

In the face of these complexities, power generating equipment designers must guarantee the service life of the parts they design or, at least, specify when these parts are to be taken out of service to prevent catastrophic failure. The problem is reduced to one of estimating what degradation will occur due to continuous load and occasional overload conditions during the operating life of a power plant.

While the task may seem overwhelming, engineers are not without help. Here, specifically, past experience is a major resource used in the design of new equipment. Yet, higher operating temperatures and greater loads have become a way of life in the electric power industry, and past experience can only carry an engineer so far. Laboratory testing also provides useful information, but even a 5,000-hour test program, which can easily take over a year to complete, requires that extrapolations by factors of 10 or 20 be made to achieve design-oriented goals. The applicability of these results for equipment that must last 100,000 hours is an ever present concern. It is obvious that new means of accounting for the many effects which high temperature, high strains, long operating times, and adverse environments introduce must continue finding their way into design practice.

It is in this regard that the NASA Lewis Research Center has been active over the past two decades. NASA's role in this area has been one of providing widely applicable predictive tools that can be tailored to specific needs. General Electric, for example, used NASA-derived parameters for high temperature low-cycle fatigue to evaluate data on AISI types 304, 316, and 348 stainless steels (Berling and Slot, 1969). Figure 2-2 illustrates the GE test results, compared with fatigue curves obtained from

empirical formulas developed by S. S. Manson and G. Halford at Lewis. This work contributed in an important way to a program on low-cycle fatigue properties of temperature-resistant materials sponsored by the U. S. Atomic Energy Commission for the development of fast breeder reactor technology.

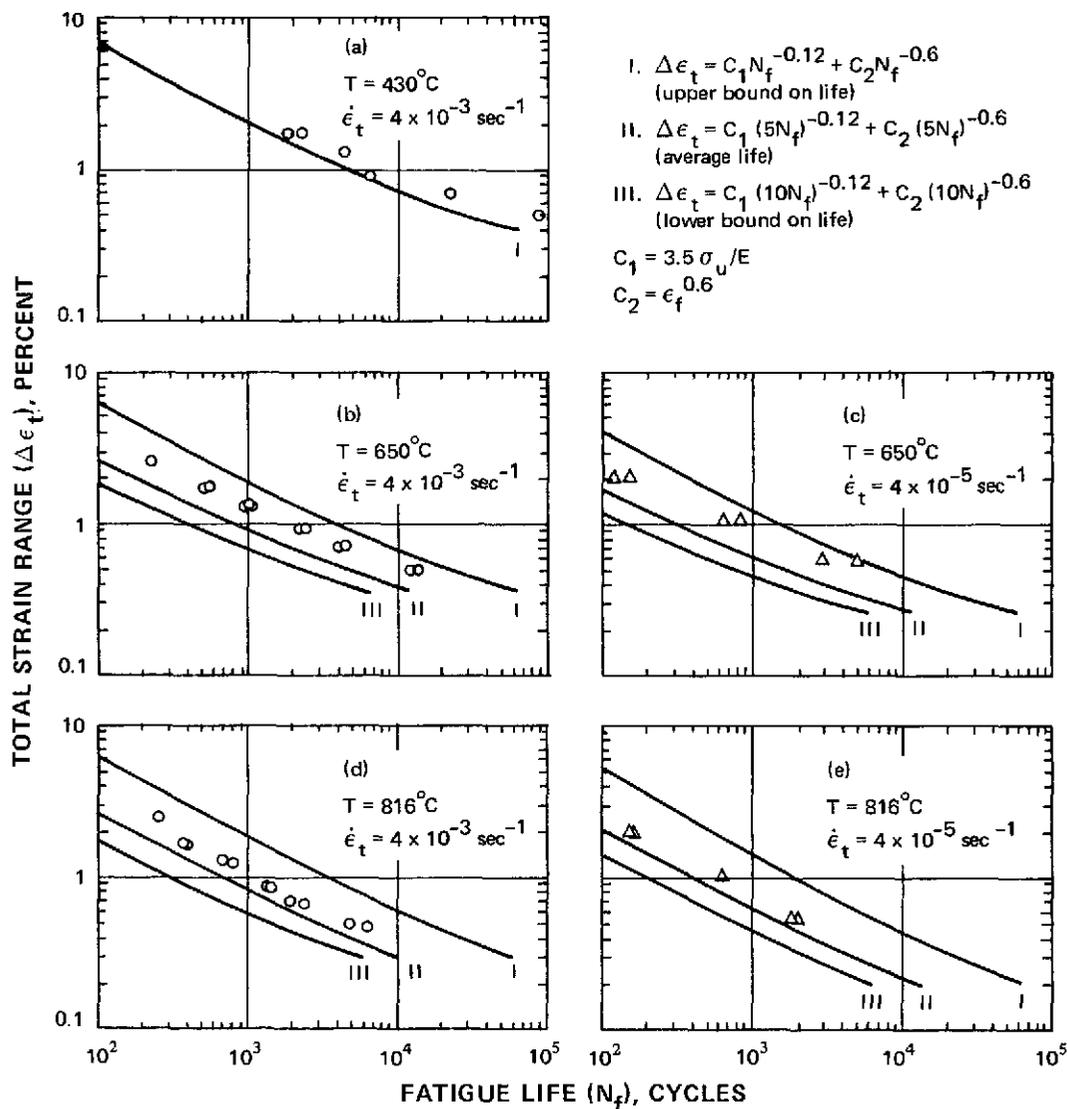


Figure 2-2. Comparison of Fatigue Test Results for AISI 316 Stainless Steel with Fatigue Curves Predicted by Manson-Halford Procedure. [Source: Berling and Slot, 1969.]

NASA researchers along with many others have been acutely interested in the development of predictive time-temperature parameters over the past two decades. A time-temperature parameter is an analytical expression which can be used to calculate the stress to produce rupture in a given time at a

given temperature. The importance of these parameters is that they facilitate prediction of 100,000-hour equipment performance based on test programs of 5,000 to 10,000 hours (Manson, 1969).

One of the first of these, the Manson-Haferd parameter, was developed at Lewis in 1953. A typical application involves Combustion Engineering, Incorporated, in Chattanooga, Tennessee, which uses the Manson-Haferd parameter as one of its standard methods for analyzing stress-rupture data for new alloys. The company's steam generators for electric power plants are designed according to the ASME Boiler Code, which specified material and processing standards for the many steam generator components. In order to receive a code-stamped approval on a unit, the company must have each new material used in the steam generator approved by the relevant ASME code committee. The company saves considerable test time by using the Manson-Haferd parameter to evaluate new alloys for applications such as boiler tubing. This approach allows Combustion Engineering to accelerate the improvement of its steam generators with new alloys while complying with the ASME code committee approval process (Smith, 1973).

Through the years, investigators at Lewis have participated in the numerous professional activities held by the American Institute of Mining and Metallurgical Engineers, the American Society for Metals, the American Society for Testing and Materials, and the American Society of Mechanical Engineers. By serving on professional committees, providing test data and computer time to committee activities, and presenting technical papers both in the United States and abroad, Lewis personnel have disseminated the results of their materials research to design engineers throughout the world (Manson, 1972).

One example of the wide-spread impact of this effort is found in the design codes which provide the criteria for receiving an ASME Code Stamp. In many states, this stamp is required by law for classes of operating equipment where failure would have serious consequences. Even when not required by law, the procedure is often followed by equipment manufacturers as part of their best practice. In 1964, the ASME published a high temperature code (Code Case 1331) to provide design criteria for materials operating at temperatures above 800°F. This code case has undergone seven revisions as advances were made in the understanding of high temperature fatigue. In 1970, the linear life-fraction damage rule was incorporated into the code case as a means of assessing the combined damage from creep and fatigue. This rule was first proposed about 20 years ago, but it lacked credibility until extensive tests were conducted at Lewis to demonstrate that it was a useful property estimator (Manson, Halford and Spera, 1971).

Since 1970, a more viable approach for creep-fatigue life analysis and prediction, called strainrange partitioning, has been developed and verified at Lewis. This method offers advantages not found in previous approaches, such as a reduction and simplification of the laboratory testing needed to characterize completely the creep-fatigue behavior of a material at elevated temperatures. More accurate predictions are now possible, since the variability of the creep life fraction computation is reduced (Manson, NASA TM X-68171, 1972). The Argonne National Laboratory has used strainrange partitioning to correlate its data on stainless steel and found it to be better than any other approach (Diercks and Kitagawa, 1972). Strainrange partitioning is also used to establish realistic bounds on cyclic life that are specifically tailored for any type of service loading cycle (Halford, Hirschberg, and Manson, 1972). A position paper which introduces some of the features of the strainrange partitioning approach has been prepared for the ASME Subgroup on Elevated Temperature Design, which is looking toward the eighth revision of Code Case 1331 (Halford, 1973).

Code Case 1331 is presently applied to the design of high temperature gas-cooled reactors (HTGR), liquid metal fast breeder reactors, steam generators, gas turbines, and other high temperature systems. Gulf General Atomic Corporation, for example, is using Code Case 1331 and the Manson-Halford creep fatigue parameters in the development and design of 1,000-megawatt HTGR power plants (Jakub, 1973). Likewise, Combustion Engineering, Incorporated uses the creep-fatigue criteria established in Code Case 1331 in the design of tubing for power plant steam generators (Smith, 1973).

Although other examples could also be cited, it is more important to comment on the overall significance of the NASA contribution than to continue a litany of impact. The high temperature behavior of materials is an immensely complex subject—one which has few uniformly accepted design criteria. Therefore, it would be misleading to imply that NASA contributions to this field have been universally accepted, especially since most experts in the field doubt that there will ever be a single approach to all of the problems of high temperature design. Yet, in a climate where new power generating equipment continually demands improved analytical capabilities, valuable alternatives have come from the R&D conducted by NASA.

### Combustion Engineering

In both powered flight and in the generation of electricity, the technology for controlled release of thermal energy is of fundamental importance. Non-nuclear production of electrical energy begins with the combustion of fossil fuels: in particular, coal, heavy oils and natural gas. Jet aircraft burn light, high-grade fuels (kerosene) as do a number of familiar rocket engines including the huge Saturn booster. Since these fuels are all members of the hydrocarbon family, there is a common theoretical basis in thermodynamics, thermochemistry, and reaction kinetics that links the performance of steam generators, turbines and rockets.

It might appear that this commonality is overdrawn because of the enormous differences between a boiler designed to operate for forty years and a rocket engine designed to operate six minutes. The fact is, however, that the commonality is understated. Only the engineering and functional differences, together with clearly separate paths of industrial evolution mask the fact that the same physical laws governing combustion are operating in both spheres.

The problem of reducing emissions composed of various oxides of nitrogen ( $\text{NO}_x$ ) from stationary power plants provides an illustration of just how theory affects practice. The Clean Air Act Amendments of 1970 addressed the role of  $\text{NO}_x$  production by stationary power plants in the creation of photochemical smog. Some 45 Air Quality Control Regions, established in 29 states (see Figure 2-3), were classified as Priority I, which means that the production of  $\text{NO}_x$  from stationary power plants must be curtailed drastically in these regions (Hauser and Shy, 1972). Several state and local governments have also enacted air quality standards which require sharply reduced admissible  $\text{NO}_x$  emissions by 1975.

PRIORITY - I NO<sub>2</sub> REGIONS



Figure 2-3. Priority Areas for NO<sub>x</sub> Reduction. [Source: Hauser and Shy, 1972.]

Local utilities are confronted with a problem of incredible magnitude: how can emission control be established without starting all over, perhaps with an entirely different power production technology. The combustion of NO<sub>x</sub> in stack gases is determined by the history of the gases as they move through the furnace. Two fundamental problems in meeting the new NO<sub>x</sub> standards for stationary power plants are: understanding the exact nature of NO formation in the furnace and how to adjust combustion techniques to reduce NO without significantly increasing the emissions of carbon monoxide, hydrocarbons and smoke (Satterfield, 1972). Basic aerospace research in the field of propellant combustion has produced the analytical tools required to address both problems. In a relatively short time, substantial progress has been made toward compliance with NO<sub>x</sub> emission standards through the application of these tools.

As recently as 1963, the most attractive industry approach to the reduction of nitrogen oxide was thought to be a high temperature catalytic-conversion method (Energy Study Group, 1964). This method was found to be impractical during the intervening years. It has been established that if the flame temperature in a furnace is maintained below 3,000° F, NO<sub>x</sub> formation is dramatically reduced. The direct approach, then, is to control the combustion process in a boiler so that the flame temperature remains below this peak reaction zone temperature (Seabrook and Breen, 1972). This approach requires a sophisticated analysis of the nonhomogeneous combustion process for each combination of fuel, boiler equipment and operating environment. An analysis of this type involves the aggregation of localized models that describe fuel vaporization, chemical kinetics and equilibrium products. These operating conditions which correspond to maximum NO<sub>x</sub> reduction and minimum

performance degradation are thus identified and then tested in the boiler itself. Manipulation of combustion temperatures by these methods fall into several classes: delayed mixing, premixed off-stoichiometric combustion, off-stoichiometric diffusion flames (secondary combustion) and direct temperature control.

The approach described above for reducing  $\text{NO}_x$  emissions was developed by KVB Engineering, Incorporated, a Tustin, California consulting firm. KVB was formed in 1970 by a group of aerospace combustion experts for the purpose of adapting combustion analysis techniques developed for the space program to industrial applications. The company has initiated or completed boiler analyses for eight electric utilities with resulting  $\text{NO}_x$  reductions ranging from 40 to 70 percent (Breen, 1972). No known alternative approach to solving the  $\text{NO}_x$  emission problem for stationary power plants appears to be comparable in cost or effectiveness to the KVB methods. Several utilities have initiated programs to modify their boilers in accordance with the KVB recommendations. Although the initial success has been primarily with gas-fired units, experiments have also demonstrated similar  $\text{NO}_x$  reductions for oil- and coal-fired units. KVB is also working with a major steam generator manufacturer to incorporate its new techniques for flame temperature control into the design of a new furnace which will offer significant improvements in  $\text{NO}_x$  emission control and combustion efficiency.

A typical reduction of  $\text{NO}_x$  that can be achieved through flame temperature control was reported by the Southern California Edison Company in Los Angeles, which was the first utility to use the KVB service. The company has reduced  $\text{NO}_x$  emissions by 50 to 70 percent in each of its 22 natural gas-fired boilers through the use of two combustion techniques from KVB: exhaust gas recirculation and secondary combustion. These reductions were achieved without degradation of plant operation, efficiency or safety. Eight oil-fired boilers are also being converted to use the two techniques. By using the KVB methods, the company expects to be in compliance with the Los Angeles County air pollution standards long before the 1975 deadline (Rosenthal, 1972).

The importance of these new methods is illustrated in the following examples. When construction began on Los Angeles' Department of Water and Power's new Scattergood Unit 3, there were no legal restrictions on emissions of nitrogen oxides ( $\text{NO}$  and  $\text{NO}_2$ ). A subsequent law—Rule 67 of the Los Angeles County Air Pollution Control District—sets the 1975 limits for such emissions at 140 pounds per hour (calculated as  $\text{NO}_2$ ). In the original unit design, the manufacturer guaranteed a maximum  $\text{NO}_x$  emission of 350 ppm (approximately 1,500 pounds per hour) at 460 Mw. The manufacturer, in a supplemental agreement, added flue gas recirculation and an overfire air feature. This resulted in a guarantee of 250 ppm (approximately 1,100 pounds per hour), still eight times the emission allowed by Rule 67 (Sonderling, 1972). The department had spent \$6.5 million on construction and signed contracts totaling \$24 million for equipment when a construction permit was denied on the basis of these anticipated  $\text{NO}_x$  emissions. In a subsequent appeal to a state court, the permit denial was upheld.

The department was granted the permit only after it agreed to implement operating changes designed for them by KVB. The additional pollution control equipment will cost \$2 million, as compared to the total plant cost of \$68 million. This plant will be the first constructed under the new law. Scattergood Unit 3 is scheduled to start producing almost 10 percent of Los Angeles' electricity in 1974. Most of the department's 17 other boilers are being converted to use the same techniques before the 1975 deadline (Sonderling, 1973).

The three standard analytic tools used by KVB in its work are: a fuel vaporization model, a chemical kinetics computer program, and a chemical equilibrium calculation computer program. Each of these tools was developed by NASA's extensive combustion research program for rocket propulsion systems.

The vaporization model was developed at the Lewis Research Center to provide local vaporization rates, mixture ratios, and combustion conditions for numerous combinations of propellants, engine design parameters and operating parameters. This permits the nonhomogeneous conditions in a combustor to be modeled locally. The heat and mass transfers that occur between introduction of a fuel and final combustion are included in the model (Priem, 1972). A NASA Technical Report (NASA TR R-67) describing the model was published in 1960. The Dynamic Science Division of Marshall Industries, under contract to Lewis, subsequently improved the model and prepared a corresponding computer program. This research eliminated the need for several assumptions that were used in the original model. Many of the combustion experts at KVB were formerly associated with Dynamic Science (Kosvic, 1973).

After the vaporization process is modeled, the chemical kinetics of combustion gases must be analyzed. Computer programs are used to calculate the chemical kinetics of exhaust gas expansion characteristics. The performance of different combustor geometries and combusting techniques can be analyzed in this way. Several important chemical kinetics programs were developed for NASA rocket research at TRW Systems in Redondo Beach, California, under contract to the Manned Spacecraft Center, and at the Lewis Research Center.

The TRW programs, for example, calculate the expansion of combustion produced gaseous mixtures, including condensed products, for different fuel compositions, combustion temperatures, relaxation rates and nozzle geometries. The calculation method (second order implicit integration) permits computation times that are two or more orders of magnitude less than standard explicit methods. These programs were subsequently standardized and refined for the Interagency Chemical Rocket Propulsion Group (ICRPG) to provide a one-dimensional and a two-dimensional chemical kinetics program. The combustion expert who developed the TRW programs later served as the Theoretical Working Group chairman for ICRPG and is currently the president of KVB Engineering.

The ICRPG was formed in 1966 to standardize analytical computer programs for the aerospace industry and adapt them for general use. Four working committees were established, involving 60 experts, and bimonthly meetings were held for the next three years to review the numerous computer programs that had been developed. Five programs were selected as the most useful for adoption as industry standards (titles abbreviated):

- *One-Dimensional (Equilibrium)* developed at Lewis Research Center;
- *One-Dimensional (Kinetic)* originated at TRW, Incorporated, developed under NASA funding;
- *Turbulent Boundary Layer* initiated at the Jet Propulsion Laboratory, developed under NASA contract;
- *Two-Dimensional (Equilibrium)* initiated at the Jet Propulsion Laboratory, developed under NASA contract; and
- *Two-Dimensional (Kinetic)* originated at TRW, Incorporated, developed under NASA funding.

These programs have been improved and generalized, under ICRPG sponsorship, to become standard analytical and design tools for broad classes of aerospace combustion problems (Kliegel, 1972). The revisions of the one-dimensional equilibrium program were conducted at the Lewis Research Center where it originated.

The final step, calculating the chemical equilibrium composition of exhaust gases, is crucial for an analysis of the combustion process. Lewis Research Center has conducted extensive research in this area for the last 25 years. The Lewis program referred to above is called Chemical Equilibrium Calculations (CEC). It has become one of the most widely used programs of its type in the United States. This program is routinely used at KVB as the final step in analyzing the amount of  $\text{NO}_x$  in boiler exhaust gases.

After devising a practical calculation technique in the 1950's for high temperature chemical reactions with numerous products, Lewis researchers continued to update, generalize, and refine the basic CEC program. By 1971, CEC had become independent of the particular computer used; accurate with a built-in restriction from printing incorrect answers; general to the point that most chemical systems could be analyzed; and modular so that unnecessary subroutines for a particular problem could be bypassed. Constant volume, detonation, and shockwave phenomena could also be analyzed with CEC.

The wide scope of these developments exceeded the specific NASA requirements. This was done, in part, as a "community service" so that expanding computer capabilities could be utilized in equilibrium calculations by a large community of interest. The basic thermodynamic data used as input to CEC can be obtained from Lewis for over 500 chemical species or generated by the user with another program (PAC-II) developed at Lewis. NASA announced the availability of the CEC program in Tech Brief 68-10025 and, in 1971, distributed a Special Publication (SP-273) which presented the program documentation along with several topics of general interest for chemical equilibrium analysis (Gordon and McBride, 1972).

During the last five years, almost 200 scientists and engineers from universities and industrial firms have requested the program from the Lewis Center; and the one area of application that is particularly significant now concerns the use of the program as a tool in general pollution control. The Babcock and Wilcox Company, a leading producer of power plant equipment, has been using the chemical equilibrium program for about two years. The program is used in the company's development of techniques to reduce  $\text{NO}_x$  production from their furnaces and equipment for  $\text{SO}_2$  removal. Both applications are for fossil-fueled generating plants. For  $\text{NO}_x$ , the program is routinely used to calculate the effects of changing the combustion variables such as temperature, air and fuel quality. This provides a guide in their investigation of hardware design changes to reduce pollutant emissions. For  $\text{SO}_2$ , the program is also routinely used to investigate the various chemical reactions associated with the sulfur recovery system for several types of  $\text{SO}_2$  removal equipment which are under development (James, 1973).

### **Process Control**

Historically, the basic industries, such as electric power, petroleum, chemical, steel, aluminum, and communications, have relied on the development of higher performance equipment for use in more complex systems in order to expand production capabilities. Reliable and economic operation of such equipment has, in turn, depended upon advances in process control technology. With the

stringent aerospace performance requirements, the development of modern control technology has been accelerated, and many space program innovations are now being used in these basic industries.

One of the first automatic controllers, a steam engine governor, was developed by James Watt in 1769. Watt's governor contained the three essential features of modern automatic controllers in a simple mechanical device: a sensing element to measure the controlled variable (shaft rotational speed); a power element to adjust the controlling variable (engine throttle setting); and a "computer" element which processed the measurement to provide an adjustment.

While all three of Watt's major controller elements have been substantially refined, the most dramatic changes since 1940 have been related to the use of analog and digital computers. During World War II, the need for greater precision in weapon systems control led to the development of single-loop feedback control servomechanisms that were based on a new understanding of the computer's processing function. With the advent of the feedback concept, control design based on computer analysis and mathematical modeling of the operating unit quickly evolved, and the basic discipline of control technology rapidly changed from mechanical to electrical engineering. By 1960, the analog computer had become a major tool in control design and a component in many control systems. For design work, it has been used to simulate, or model, the operating system and its controllers. By using this technique, better performance was achieved for much lower design costs (Oldenburger, 1965).

For the last fifteen years there has been a trend toward using the more versatile digital computer in both control design simulation and in operational control systems. In design, the digital computer provides the basis for implementing a new approach to solving control problems. This approach has its origin in the development of optimal controls for rocket guidance systems. For example, by analyzing a mathematical model using optimal control theory, design engineers can develop the "best" control system for a specific application. Much of the current academic and industrial control theory research is in the development of techniques for more accurate mathematical models which incorporate the nonlinear, indeterminate aspects of real operating equipment (Takahashi, Rabins and Auslander, 1970 and Oldenburger, 1965).

As a control system component, the digital computer provides complex systems with adaptive control capability for faster and more accurate response to changes in operating conditions. Process industries were among the first to require simultaneous control of several operating variables, which became possible with digital computers. By mid-1968, the electric power and aerospace industries were the leading users of process control computers, with 292 and 252 installations, respectively, out of over 1,600 digital process computers on order or installed in this country. These totals include off-line information processing applications as well as open-loop and closed-loop control (U. S. Department of Labor, 1970). One major supplier of control equipment estimates that the market growth for process computers in electric power applications will continue to be about 20 percent annually (Jarvis, 1972).

Two major types of computer control applications in the electric power industry are power transmission and power generation (Ryan, 1966). In both applications, electric utilities are switching from the standard analog units to digital-directed analog and direct digital control in response to the demanding performance requirements of interconnected transmission systems, larger generating plants and nuclear reactor plants. Three important functions for transmission system computers are:

real-time matching of the alternating current frequencies from different generators in the network (load frequency control); real-time response to restore system stability after severe disturbance (system security); and the assignment of output levels for the various network generating plants to meet the changing total load demand while minimizing the total generating costs (economic dispatch) (Lamont and Tudor, 1970). A number of electric utilities, responding to the increasing complexity of transmission systems during the 1960's, conducted studies related to the use of computers for system security, and the number of digital computer installations for this purpose is increasing substantially. The Federal Power Commission also conducted an extensive examination into expanding the use of real-time digital computers for system security following the 1965 Northeast Blackout (Brown, 1966).

Most large boiler-turbine-generator sets include computers for startup and shutdown sequencing, performance monitoring, and on-line control; for nuclear reactors, computer control is crucial (Ryan, 1966). In these applications, computer controls provide better performance and decrease the chance of human error in operating the complex equipment. Fully automated power plant control systems, however, are still under development.

Two NASA contributions to control technology are described below, together with examples illustrating their application in real-time power grid control and optimal power plant control. The first contribution was part of the Apollo Guidance Computer system, and the second was included in a general computer program for numerically solving system theory problems.

**Apollo Guidance Computer.** Guidance computer engineering is a simultaneous effort in mechanical, electrical and logic design disciplines. Whereas commercial computer designers strive to maximize answers per month, guidance computer designers seek the capability of handling high peak loads as well as providing answers per second. The Apollo Guidance Computer (AGC) was designed in the early 1960's at the Massachusetts Institute of Technology, under contract to the Manned Spacecraft Center, to be incorporated into the Guidance and Navigation Systems in the Command and Lunar Excursion Modules. Its functions were: (1) to aid in operating the inertial and optical subsystems; (2) to provide steering signals where human reaction is too slow; (3) to perform spacecraft attitude control with minimum fuel expenditure; (4) to maintain timing references; (5) to communicate with the astronauts via display lights and keyboard, as well as with ground tracking stations via digital links; and (6) to calculate position and velocity relative to the earth and the moon.

The AGC was designed to employ certain so-called supervisory programs, such as the Executive, which organize the guidance computer processing in real time. The functions of the Executive are to control priority of jobs, to permit time sharing of erasable storage, and to provide a display discrete signal denoting "Computer Activity." A job is specified by its starting address and another number which gives it a priority ranking. As the job runs, the Executive periodically checks to see if another job of higher priority is waiting to be executed. If so, control is transferred away, and the job is temporarily suspended until it again becomes the one with highest priority. These periodic priority checks require less than 20 milliseconds, and up to 10 jobs may be scheduled for execution or may be in partial stages of completion at one time. All AGC programs operate under control of the Executive routine except those which are executed in the "interrupt" mode (Hopkins, 1966).

TRW Systems in Houston, Texas conducted the preflight testing of the AGC, under a Manned Spacecraft Center service contract, and verified that it met the mission profile requirements. During the course of this work, TRW computer experts became familiar with the Executive program and its real-time priority scheduling capabilities.

Another TRW, Incorporated company, TRW Controls in Houston, Texas, is a major producer of automatic computer controls for petroleum processing, pipelines, and the electric power industry. Since 1954, TRW Controls has installed more than 200 computer control systems. Approximately 25 TRW Systems computer experts have been under subcontract to TRW Controls since 1970 to develop control system programs for these applications.

One result of this effort is a new priority scheduling program, the TRW Executive, for electric power transmission system control computers. The previous experience and familiarity with the AGC Executive was fundamental to the development of this new program which extends the real-time processing capabilities of commercially available batch monitors.

The TRW Executive is now a standard program in the company's large, new monitoring and control system for power transmission applications. This system provides automatic control for circuit breakers and small changes in generator output and frequency. The first of these systems was installed for the General Public Utilities Corporation, which serves 1,300,000 customers in a 25,000-square mile area of Pennsylvania and New Jersey. Three more of the systems are on order or are being installed for electric utilities.

In addition to the Executive program, the new TRW control system includes state estimation programs for economic dispatch. These were adapted from similar programs developed at TRW Systems for calculating targeting routines in the Lunar Module Abort Guidance Computer (Jarvis, 1972 and Woodruff, 1973).

**Automatic Synthesis Program.** The Automatic Synthesis Program (ASP) was developed between 1963 and 1966 at Martin-Marietta Corporation in Baltimore, Maryland, under contract to the Ames Research Center. One of the principal investigators on this contract was R. E. Kalman, a major contributor to the development of optimal control theory. As a result, ASP was created to be an efficient analytic design tool for control systems, including optimization of linear dynamic systems. It has been successfully used on several reentry and lunar landing control problems, aircraft control, and control of large flexible booster rockets. Both the program and the user's manual, NASA CR-475, are designed to be easily understood and used by anyone with a background in modern system theory, including the novice in optimal control theory. Examples and mathematical derivations are included in the manual, making it valuable as a textbook on optimal control design.

ASP consists of an executive program and thirty subroutines which can be conveniently used to solve most, if not all, linear problems encountered in the application of system theory. These subroutines are sufficient to solve the most general optimization problems for the standard formulation of linear dynamic system models. Many nonlinear models may also be analyzed by either using the mathematical technique of linearization or the iterative use of ASP subroutines to approximate the actual solution.

By solving the control design problem, a control function, or law, can be obtained from the system model to give the best control strategy based on the known system dynamics and performance index. Whereas previous control design techniques required the design engineer to select the controller structure first and then try to get the best available performance by selecting controller settings (the system parameters), optimal control theory requires no prior assumptions regarding the controller structure. ASP provides a subroutine for solving matrix differential equations of the Riccati type that result from combining the mathematical model for a system and its performance index equation. This is the key step in determining the control function for a system (Kalman and Englar, 1966, Takahashi, Rabins and Auslander, 1970 and White, 1973).

Control researchers at Drexel University and the Philadelphia Electric Company have developed one of the first applications for linear optimal control theory to boiler-turbine-generator control design and analysis. A nonlinear mathematical model for the most common type of fossil-fueled steam generator plant was created for this purpose and extensively verified by tests. The model was then linearized, and the Riccati Equation subroutine from ASP was programmed to solve for the control law. Simulation tests have been conducted to compare the proposed new control strategy with the existing control structure in a 200-megawatt plant, and improved performance was demonstrated. The new strategy will produce controller action which guarantees optimum load-following capability.

The exact operating conditions in the target plant are being defined to determine what degree of performance improvement can be realized. This is preparatory to implementing the control strategy in an actual, direct digital control application. Eventually, the target plant will be automatically controlled to follow the load requested by a power grid dispatch computer (McDonald and Kwatny, 1972 and McDonald, 1973).

The significance of this experimental program lies in the fact that an operating plant is not able to maintain its optimum performance as the power demand changes. If a one percent gain in net efficiency were to be realized through the development at Philadelphia Electric, this would represent a net reduction of almost three percent in fuel requirements. The importance of an improvement of this magnitude is illustrated by the fact that the Electric Research Council assigned a priority of "very important" to the development of dynamic optimization control technology (Electric Research Council, 1971).

### Summary

This section has attempted to illustrate some of the subtle ways that seemingly unrelated industries share in technological gains. While it is certainly not an exhaustive treatment, the study does show that the nature and role of engineering disciplines as linking mechanisms are crucial to industrial progress.

The investment in central power plants is staggering: a new 300-megawatt coal-fired generating station costs in the neighborhood of 65 million dollars. Only a few years ago, a 300-megawatt turbine-generator was considered a giant. Today 1,000-megawatt units are typical, and 10,000-megawatt stations are being contemplated for the future. Between 1965 and 1973, the annual capital expenditures by electric utilities for electricity generation increased from less than \$2 billion to more than \$11 billion. Over half of the 1973 amount is for fossil-fueled steam and gas turbine units (*Electrical World*, March 15, 1973). The scientific and engineering developments discussed in this section comment directly on the size, life,

efficiency, and environmental considerations that are part of the electric power industry now and will continue to be in the future.

Each of the technical areas described in this section illustrate how NASA's contributions to an underlying technology are being applied to specific problems in the electric power industry. The next section provides a more general discussion of how engineers and managers learn about these contributions and what patterns of use characterize their subsequent adaptation.

**SECTION III. DISSEMINATION AND UTILIZATION OF NASA TECHNOLOGY**

In an earlier study by the Denver Research Institute, one of the major conclusions was that "technology, rather than products, was by far the most important contribution of aerospace programs" (Welles, 1963). This is especially true in the electric power industry, where the impact of aerospace technology far overshadows the impact of aerospace products. The tangible payoff comes when this technology is embodied in new and better products and processes through more skilled engineering and practice.

This process of technology utilization poses many questions. What are some of the ways that managers and engineers in the electric power industry learn about aerospace innovation? How is this technology adopted and adapted by manufacturers of power generating equipment? How is new technology brought into the industrial market place? This section attempts to provide some insight into these questions.

**The Flow of Information About NASA Contributions**

Many direct and indirect communication links serve to connect nonaerospace users with NASA-generated technology. The Agency itself, as part of its legislative mandate, provides wide dissemination of its R&D results outside the aerospace sector through formal publications, conferences, dissemination centers, Tech Briefs and other vehicles. Further, aerospace technology is made available to the nonaerospace community through traditional channels such as activities sponsored by professional societies and trade magazines and through unplanned actions such as the transfer of people. This section will selectively review four of the many channels in operation—conferences, NASA Regional Dissemination Centers, standards and codes, and the transfer of trained professionals.

**Conferences.** Throughout its fifteen-year history, NASA has used the conference as a direct and timely method for enhancing communications among members of specific groups aligned by common scientific and technical interests. The Agency has sponsored hundreds of conferences dealing with such diverse topics as fire safety, urban technology and remote sensing applications. Further, NASA has joined professional organizations such as the American Society for Mechanical Engineers, the Institute of Electrical and Electronics Engineers, and the American Chemical Society in providing other forums for the description and evaluation of technological gains.

A special technology utilization conference on "Selected Technology for the Electric Power Industry" was held at the NASA Lewis Research Center in September 1968 to acquaint that industry with relevant scientific and engineering developments from the space program. The topics were selected with the advice of technical representatives from the industry, and Lewis staff members presented technical reviews in an industrial context. Over 200 people representing manufacturers, utilities, and associations attended the conference (NASA SP-5057, 1968).

Several of the individuals attending the conference were interviewed in 1972 to develop an understanding of the general impact of this conference, particularly from the viewpoint of the utility representatives. The role of the conference in expanding perspectives and defining new technical alternatives was indicated by the general discovery that aerospace R&D was a new resource for technical problem-solving. The conference initiated requests for basic documentation on energy conversion technology, as well as related engineering and research investigations. For example, a manager with the

Boston Edison Company obtained a NASA publication on boiler instabilities after hearing about the research at the conference. A preliminary engineering study has indicated that the technology would be useful in analyzing the company's boiler performance. Further investigations are planned to develop specific applications. (See "Electric Power Industry Conference" Transfer Example Summary in Attachment IV.)

After exposure to information concerning advances in fracture mechanics, the Detroit Edison Company sent engineers to Lewis Research Center in 1969 to attend a conference on "Aerospace Structural Materials." The company is now planning a program for the fracture toughness testing in order to devise better inspection procedures. These procedures relate to problems in equipment failure and maintainability. (See "Fracture Mechanics" Transfer Example Summary in Attachment IV.)

**Regional Dissemination Centers (RDC's).** NASA's five Regional Dissemination Centers help users in both the public and private sectors obtain information on new technology in ways tailored to their specific needs. The RDC's primary information source is a computerized data base of over 800,000 scientific and technical aerospace reports. This data base is supplemented by abstract services in specific areas such as chemistry, engineering, electronics, plastics and metallurgy.

Many companies in the electric power industry have utilized the services of RDC's to help fill their scientific and technical information needs. The Western Energy Systems Transmission (WEST) Associates is a consortium of 24 power companies formed to promote mutually beneficial interaction on common technical problems. For over two years, WEST has had an ongoing program with the Technology Application Center (TAC)—the RDC located at the University of New Mexico—to link these utilities with aerospace R&D. TAC has provided the consortium with retrospective information searches and monthly current awareness updates in the areas of air pollution and water pollution. Specific searches on topics such as "Fly-ash Utilization" and "NO<sub>x</sub> Detection and Abatement" have also been prepared for individual members of WEST (Long, 1973).

**Standards and codes.** In a very fundamental way, standards are the silent language of commerce. Pipeline networks and electrical power grids, built according to national standards, distribute essential energy; safety standards delineate the requirements for a safe home and work environment; and modern communications rely on standard symbols, drawings, magnetic ink characters and computer languages. The benefits of standardization provide: enormous savings for industry; greater safety, convenience, and lower prices for consumers; and a better functioning system for national and international commerce.

The entire span of today's knowledge of materials testing, for example, is reflected in the reference works of the American Society for Testing and Materials (ASTM)—the world's largest nongovernment standards-generating body. *The Annual Book of ASTM Standards* contains over 4,300 test methods which have been developed by the ASTM technical committees. Scientists, engineers, architects, and builders all over the world depend upon the ASTM Standards for authoritative information in all aspects of evaluation and specification of materials. In 1970 alone, over 190,000 individual volumes of the ASTM Standards were sold.

The method for fracture toughness testing developed by NASA has become the ASTM Standard Method E 399-72. The significance of the test method has been profound. Not only has it been incorporated in the ASTM Standards, but it has also been adopted by the Society of Automotive Engineers and the British Independent Steel Producers Association and has been included in the *MIL*

*Handbook-5.* The engineering community has literally adopted the  $K_{IC}$  designation as its primary way of speaking about fracture toughness.

In a similar way, codes have strongly influenced engineering practice, especially where safe design is of paramount importance. Probably the best known and most widely used engineering code is the American Society for Mechanical Engineers (ASME) Boiler Code. The ASME Code for Construction of Boiler and Pressure Vessels, first published in 1914, is given major credit for the steady decrease in boiler explosions since that date, even though the number and size of boilers in use have increased tremendously.

In recent years, the code has rapidly expanded, reflecting the proliferation of technological developments which have occurred. In the larger sense, the influence of NASA technology on the Boiler Code has been specialized. Yet, this influence is growing, especially in important areas of nontraditional design such as the high temperature design code (see Section II).

Today, the ASME Boiler and Pressure Vessel Code has been incorporated into the laws of 70 jurisdictions—including many states, territories, and the 10 provinces of Canada. Similarly, in 1969, the British Committee on Enquiry on Pressure Vessels advocated “that a procedure, identical in all essentials to the ASME Code Case procedure, should be adopted in the U. K.” (*Mechanical Engineering*, July 1972).

**Transfer of trained professionals.** Technical skills developed during the space program have contributed to technological changes in the electric power industry through the transfer of skilled personnel. Three forms of the “people transfer” mechanism can be identified: formation of new companies serving the electric power sector by previous aerospace employees; transfer of employees within corporations which manufacture for both the electrical power and aerospace sectors; and active recruitment of skilled aerospace employees by companies which comprise the electric power sector.

KVB Engineering, Incorporated in Tustin, California was formed in 1970 by space program combustion experts to provide combustion consulting services in the electric power industry. The company has been very successful in adapting rocket combustion technology to the control of  $NO_x$  emissions from stationary power plants. (See “Computer Programs to Analyze Combustion” and “Fuel Vaporization Model” Transfer Example Summaries in Attachment IV.)

Two examples of the internal transfer of personnel are provided by TRW, Incorporated and the General Electric Company. TRW Controls, a major manufacturer of computerized process controls in Houston, Texas, has obtained approximately one-half of its 200 engineers and computer scientists from the aerospace industry. Most of these individuals transferred from TRW Systems, a major contractor for guidance control computer research and development. TRW Systems also performs industrial computer control development, under subcontract to TRW Controls, for applications such as electric power distribution network controls. (See “Apollo Program Checkout and Control Computer Systems” Transfer Example Summary in Attachment IV.) The General Electric Apollo and Ground Systems (AGS) group provided reliability and quality assurance support for the space program under a NASA service contract. Several members of the AGS technical staff have transferred to GE’s commercial product groups where they apply advanced reliability and quality assurance methods to improve electric power generation and distribution products such as steam turbine controllers and High Voltage Direct Current equipment. (See “Reliability and Quality Assurance for NASA Programs” Transfer Example Summary in Attachment IV.)

Consolidated Edison Company of New York, Incorporated and the Tennessee Valley Authority have up-graded their in-house capabilities by hiring former aerospace personnel in specific technical areas. Con Ed has started a program for reliability and quality assurance in this way (Gordon, 1973). The TVA has used this direct approach to improve welding and nondestructive testing in the agency's power plant construction projects (Willis, 1972).

#### Technology Utilization—Through Diffusion and Transfer

There are many mechanisms operating to effect secondary utilization of aerospace technology, several of which have already been cited. These mechanisms can be conventionally categorized as either diffusion or transfer processes. Table 3-1 illustrates some of the contrasting characteristics of these processes.

TABLE 3-1. CONTRASTING CHARACTERISTICS OF TECHNOLOGY  
DIFFUSION AND TECHNOLOGY TRANSFER  
AS MECHANISMS FOR INTRODUCING NEW TECHNOLOGY

DIFFUSION	TRANSFER
Professional communities aligned by technical problems bridge different sectors.	Organizations participating in planned transactions independent of sectoral alignment.
Technological constraints serve as the focus for problem-solving activities.	Application constraints serve as the focus for problem-solving activity, i.e., economic constraints.
Innovations tend to be institutionalized because they redefine best practice—stepwise improvements.	Innovations tend to have transient impact since their application represents a currently <i>optimum</i> alternative: vulnerable to a better solution as time goes by.
Ongoing, interactive communications influence sector performance.	Singular technical communications influence organizational performance.
Additional technological advancement occurs as adoption proceeds.	Little or no advancement of technology; adaptation is crucial.

The diffusion mechanism is characterized, in one way, by the movement of technology within a community of interest, aligned by professional societies such as the American Society of Mechanical Engineers, the American Society for Testing and Materials, and the Society of Automotive Engineers. For example, to assure the broadest use of their fracture testing research, NASA engineers have chosen to

communicate with the nonaerospace community primarily through the publications and activities of the American Society for Testing and Materials—particularly the E-24 Committee on Fracture Testing of Metals. Figure 3-1 illustrates this linking mechanism between two socioeconomic sectors having different purposes and functions, but areas of similar technical needs. The most noticeable characteristic of this mode of diffusion is that it bridges contemporary sectoral alignments. Engineers and scientists in professional communities associate with one another because of particular technical interests and problems, in addition to serving in organizations that make up the generally defined socioeconomic sectors (e.g., aerospace or electric power). Often these professional communities, by virtue of their technical alignment, introduce the new innovations, or “best practice,” of one sector into another sector.

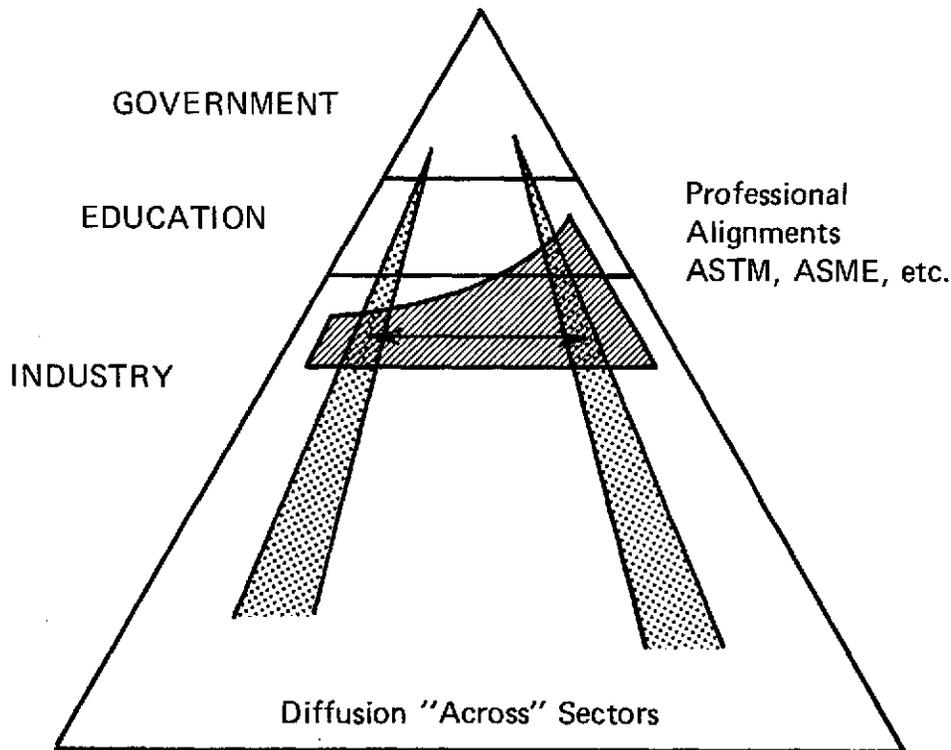


Figure 3-1. A Section Through the Societal Pyramid Showing the Linking Action of Professional Alignments that Facilitate Intersectoral Diffusion.

Technology diffusion can be contrasted with technology transfer, a mechanism which is characterized by discrete transactions. The preparation and dissemination of documentation, the movement of people, and actions of technology brokers all serve to link the originating sector with individuals and organizations outside that sector in a discrete rather than continuous fashion. Such transactions are effected by the planned efforts of the Technology Utilization Office within NASA. Figure 3-2 illustrates the technology transaction concept and the characteristic independence of the adopting organizations in terms of professional or sectoral alignment. The bulk of these transactions or transfers are facilitated by the originating sector exclusively and become systematic only through policy implementation, which results in identification, documentation, and information dissemination for new technology.

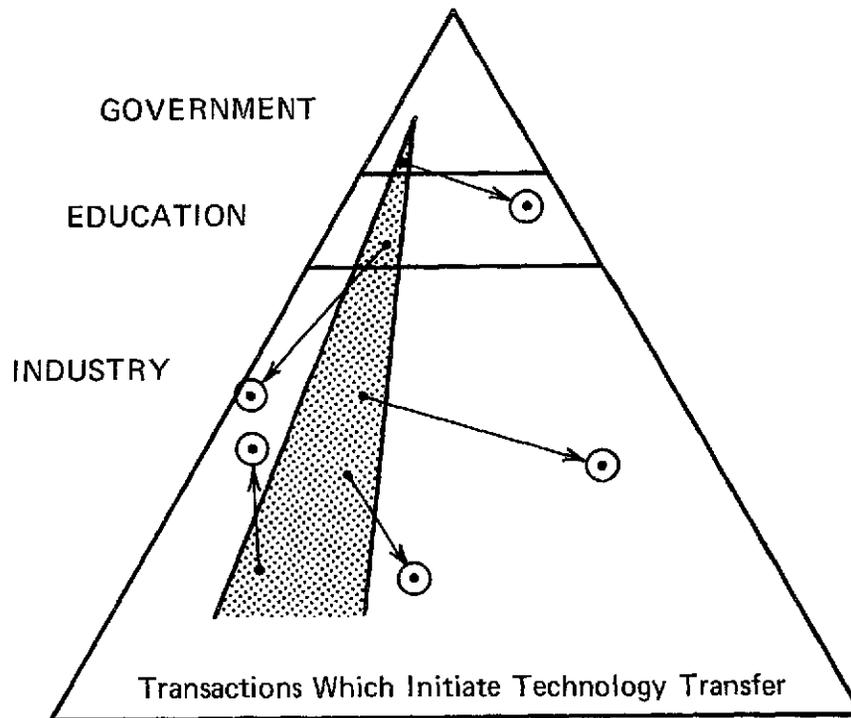


Figure 3-2. A Section Through the Societal Pyramid Showing the Transactions Necessary to Introduce New Technology in Organizations Not Aligned with the Generating Sector.

### Summary

This section has focused on some of the ways that technology, created for a specific purpose, transcends that original purpose in helping to solve seemingly unrelated problems. In some cases, it involves planned efforts by the originating organization; in other cases, it is achieved through the efforts of dedicated professionals; and in still other instances, it occurs serendipitously. In the final analysis, however, there can be little doubt that the impressive gains in this country's ability to produce electric power have benefited from venturesome aerospace research efforts.

#### SECTION IV. PERSPECTIVE

This study has brought into focus an important distinction between the ways in which technology created originally for NASA's purposes achieves secondary utilization. Most often the expectation is that nonaerospace products will in some way mirror their aerospace predecessors. This mode of technology transfer is, in general, the least common. Thus, while down-to-earth adaptations of aerospace developments such as fuel cells, solar panels, and potassium Rankine cycles may indeed be commercially achieved, a more fundamental link between the aerospace and electric power sectors already exists: a link through the engineering disciplines common to both sectors that provides both the vehicle and the environment for internalizing technological gains.

Three engineering disciplines that illustrate this link have been presented in this report: materials science, combustion analysis and systems engineering. In all three, profound and important contributions that enhance the ability to generate electrical power economically, reliably, and at a reduced environmental penalty were shown to have originated in aerospace R&D. And these contributions have been occurring for years with little fanfare because they represent knowledge that has been embodied in power generating equipment and not the equipment per se.

Thus, the evidence cited in this document suggests that advances in engineering disciplines oftentimes are more useful in nonaerospace applications than advances in new concepts for generating electrical power.

## ATTACHMENT I THE TECHNOLOGY OF ELECTRIC POWER GENERATION

This attachment presents a brief overview of the standard electric generating equipment and experimental methods which appear to have near-term potential. It is intended to provide the interested layman with a frame of reference for contemporary technological developments in the electric power industry.

A major problem in the generation of electricity is that it cannot be economically stored in large quantities; therefore, electricity must be generated as needed. The combination of fluctuating demand levels at different times of the day, week, and season and the operational characteristics of generating equipment has created the need for different types of generating units: base load, intermediate cycling and peaking power. Typically, continuous base load power generation supplies about 50 percent of the weekly maximum demand. Intermediate load, supplied for about twelve hours per day on weekdays, accounts for 30 percent of maximum demand, and the remaining 20 percent of peak load is needed from one to twelve hours each day. Large generating units used for meeting base loads are designed and built for continuous full capacity operation. They do not function well under conditions of starting and stopping—their efficiency drops drastically, and they can be severely damaged if cycled in response to changing daily demand. Some solutions to this problem have been: 1) to design base load units for short peaking duty cycles above the rated base load capacity; 2) to design peaking units specifically for quick starts and stops with variable loads; and 3) to convert older units for generating intermediate and peak power (Federal Power Commission, 1971).

### Standard Equipment

In 1972 the electricity generated in the United States was produced by fossil-fueled steam units (more than 74 percent), hydroelectric units (14 percent), gas turbines or diesel units (8 percent), and nuclear powered steam units (less than 4 percent) (Hayes, 1973). For each of these methods, electricity is produced by a generator which usually has a turbine as the driving mechanism. However, major differences occur in the types of working fluid in the turbine (water, steam or gas) and in the methods for producing fluid motion (gravity, combustion or radioactive decay). The technological development of equipment for each of these standard power generating methods is presented below.

**Hydropower.** Hydropower accounted for about one-third of the electric power production until after World War II and was extremely important in rural electrification. Since most major dam sites have already been developed (Landsberg and Schurr, 1968), its current 13 percent share is expected to decline to approximately 9 percent by 1980 (Hayes, 1973).

A hydroelectric plant uses the energy of falling water to turn a turbine and generator, thereby producing electricity with an efficiency approaching 90 percent. The conventional plant consists of a dam to hold a large volume of water, a penstock to deliver falling water to the hydraulic turbine which, in turn, converts the energy of the moving water to mechanical energy, and a generator to convert the mechanical energy to electricity. Although a hydro plant represents a large capital investment, operation and maintenance costs are low. The plants are readily automated, reliable, and free from air polluting emissions. They can be safely cycled to meet changing power demands.

The fundamental limitation on hydroelectric power generation is the limited number of sites suitable for the purpose. In addition to occupying large land areas, a hydroelectric plant must be located

where there is considerable water flow and land elevation differentials. In 1970 there were about 1,480 conventional plants with a total capacity of about 52,000 megawatts (Mw); the Western states had more than 60 percent of the installed capacity. Potential hydroelectric capacity for the contiguous 48 states is about 146,000 Mw, with about 94,000 Mw yet undeveloped (Federal Power Commission, 1971).

A second kind of hydroelectric capacity is pumped storage. A pumped storage installation uses electricity produced in the periods of low demand to pump water to an elevated reservoir; the water is then released during peak demand hours to generate additional electricity. Pumped storage is a profitable method for using the excess generating capacity of thermal plants, since the cost of pumping the water uphill during nights and weekends is less than the revenues derived from the peak period generation of the hydroelectric portion of the system (Landsberg and Schurr, 1968). In 1970 only 4,000 Mw of pumped storage capacity was installed; considering projected additions, 71,000 Mw are envisioned by 1990 (Federal Power Commission, 1971).

**Fossil-fueled steam turbines.** The leading source of electricity production in the U. S. has been the fossil-fueled steam turbine. With the vast quantities of coal resources in the U. S., this type of unit will continue to be of major importance. The primary thrust of technological advances in fossil-fueled steam generating units has been toward larger equipment, higher efficiency, greater maintainability and pollution controls.

In 1930 the largest unit in service was 200 Mw, and 95 percent of the operating units were 50 Mw or less. By 1970 the largest unit in service was 1,150 Mw, and 1,300-Mw units were being built. The average size of all units in service was near 70 Mw, and this is expected to increase to 160 Mw by 1980 as older and smaller units are retired (Federal Power Commission, 1971). These increases in plant size have resulted in cost savings through economies of scale.

Increased efficiency and greater maintainability for steam plant equipment have come about through advances in technical fields such as metallurgy, metal fabrication and instrumentation. The embodiment of these advances in steam boilers, for example, has allowed a single large boiler to replace the several small boilers that served each turbine prior to the 1940's (Belinfante, 1969). Other specific advances include:

- Automatic combustion controls;
- Electric welds rather than rivets for seams;
- Suspension burning of pulverized coal, replacing grate burning;
- Water-cooled walls;
- Better knowledge of boiler water chemistry;
- High-temperature alloy steels;
- The cyclone furnace;
- Super-critical cycle and once-through circulation;
- Longer turbine blades and better turbine blade designs;
- Hydrogen gas in generators to improve cooling and reduce windage;
- Steam reheat cycles; and
- Control equipment for turbo-generator sets and entire power plants.

In the recent past, the efficiency of fossil-fueled steam plants has leveled off at about 40 percent because steam temperatures above 1,050°F would require a stepwise increase in turbine alloy cost. This increase in capital cost for fossil steam units would not be offset by a rapid decrease in operating cost.

This situation is caused by the fact that higher temperature operation could not be employed immediately in operating units since the design of other equipment would also require stepwise advances. Two new generating methods that will use higher combustion temperatures to increase efficiency are being developed: the combined cycle and the binary cycle. In both cases a fossil-fueled, high-temperature "topping" unit is being added to a modified standard steam unit so that the amount of high cost alloy is minimized. A gas turbine is used as the topping unit in combined cycles, and this technology will be described in the section below.

In the binary cycle, a condensible liquid metal vapor replaces steam for the high temperature range (1,000°F to 1,500°F). A heat exchanger simultaneously condenses the metal vapor and generates steam for the steam cycle. From 1920 to 1960, binary cycle plants of up to 50 Mw in size operated in this country using mercury and steam, and their efficiency level was approximately 50 percent. Because of the technical and economic problems associated with the mercury portion of the cycle, their development was discontinued. Recent advances in the understanding of liquid potassium and sodium have generated a new interest in binary cycles using these materials to replace mercury. The primary advantage of liquid potassium and sodium for a high-temperature cycle is their very low (typically one atmosphere) vapor pressures at high temperature (Fraas, 1966). This greatly simplifies design problems and reduces the quantity of expensive high-temperature alloys since, for example, thin-walled boiler tubing can be used. However, great care must be exercised to isolate the liquid metal system due to the hazardous nature of water and potassium or sodium mixtures.

Finally, a significant portion of the direct R&D expenditures in power generation by the electric utilities is for the development of pollution controls to meet new standards. Two of the major goals for these developments are increased effectiveness of the equipment and reduced cost. Advances are being made in equipment which is used, for example, to remove fly ash and sulfur dioxide from stack gases, reduce nitrogen oxide formation, and condense the steam by cooling.

**Gas turbines.** Although diesel and gas turbine units have been major sources of peaking power and standby capacity, the dramatic increase during the last decade has been in the use of industrial gas turbines. From 1965 through 1969, ten percent of utilities' added capacity was in the form of gas turbine peaking units. These ground power units have become the major product for turbine manufacturers whose sales volume rose tenfold during the 1960's (Schloesser, 1969). A 1969 survey of utilities by *Electrical World* showed that 58 percent of the companies were considering installation of gas turbine units (*Electrical World*, July 7, 1969); by 1970, utilities were ordering gas turbine generating capacity at an annual rate of 9,000 Mw (*Electrical World*, February 23, 1970). The more than 500 units in use by the end of 1972 provided 28,000 Mw of capacity, which was 7 percent of the total utility capacity (Hayes, 1973). Some of the major factors which make the gas turbine an attractive generating unit are low capital cost, relatively short installation time, low pollution emissions, ease of automation, quick start-up, reliability, and the ability to operate efficiently at partial load.

The operating principle of the gas turbine is based on the idea that the expansion of hot combustion gases can be employed to produce rotary motion in a fan. Many refinements have been made in the application of this idea over the years, but its efficiency remained low until the research necessary to build aircraft jet engines yielded metallurgical and design advances that made it a practical means of energy conversion (Federal Power Commission, 1971). These advances included technology of blade cooling, materials, aerodynamic flow path design, high-heat release burners, and modular fabrication technique (Robson and Giramonti, 1971). Gas turbine efficiency, which depends upon the gas inlet temperature and compression ratio, has been steadily increased by these innovations.

In the operation of a gas turbine, a specially built combustion chamber burns liquid or gaseous fuel in an excess of air supplied by a compressor. The hot gases (typically 1,800° F) expand in the turbine stage to drive the turbine and compressor. A generator coupled to the turbine drive shaft produces electricity. Adaptations of the simple cycle increase efficiency by adding precoolers, multistage compression, intercoolers between compression stages, and regenerators which capture some of the exhaust heat to preheat the compressed air prior to combustion.

Since 1960, gas turbine generating unit capacities have increased to 60 Mw for a single turbine drive and to 160 Mw when several turbines are used to drive a single generator. Ongoing development is expected to result in a 100-Mw or larger unit by 1980; and 300-Mw units are anticipated as a future possibility. Gas turbine R&D can be expected to seek ways to reduce maintenance costs, utilize less expensive fuels, and reduce emissions and noise. Other areas of R&D interest include further improvement of high-temperature, high-strength, and corrosion-resistant alloy materials; improved combustion and combustion temperature control; and improved control and monitoring techniques (Federal Power Commission, 1971).

In addition to their peaking generation applications, gas turbines are also being used in a new combination unit called the combined cycle. This cycle includes a high-temperature gas turbine-generator unit and a lower temperature steam turbine-generator unit. Heat from the gas turbine exhaust gases (typically in the range 750°-950° F) is used to preheat steam boiler intake air or to produce steam. By using the combined units in complementary temperature ranges, the combined cycle appears to have a greater potential for efficiency gains through technological improvements than is available in either individual unit, gas or steam (Ecabert, 1966). The operational combined cycles, however, are less efficient than the best operational steam units. One major proposed application is for large base-load plants to be located near coal mines, so that the gas turbine can be fueled by gas from a partial coal gasification process.

In conjunction with high temperature gas-cooled reactor (HTGR) nuclear plants (discussed below), the gas turbine holds promise as an alternative base-load generating method. The HTGR nuclear core is cooled by passing helium through the core where it reaches 1,400°-1,500° F. Current designs include a heat exchanger between the helium and steam systems which produces high-pressure steam at 1,000° F. The alternative being considered is to eliminate the steam cycle and, in a closed system, use the helium to drive a gas turbine directly (Harmon, 1973).

**Nuclear power.** A nuclear plant, like the hydroelectric plant, has a high capital cost. However, both are competitive with fossil-fueled plants because they incur sharply lower operating costs. The Federal Power Commission has noted that doubling the capital cost of a nuclear plant from 1965 to 1970 did not eliminate the competitiveness of nuclear power because nuclear fuel costs did not rise, while both capital and operating costs for fossil-fueled plants rose appreciably (Federal Power Commission, 1971).

Only 6,000 Mw of nuclear capacity were installed by 1970. However, a capacity of more than 140,000 Mw is projected for 1980, with a possible 500,000 Mw by 1990. This would constitute 40 percent of the total projected installed capacity at that time (Federal Power Commission, 1971).

The development of nuclear power technology has concentrated on the fission reactor, which converts nuclear energy to thermal energy for a steam cycle. The controlled fission chain reaction

utilizes the energy released by nuclear fission and by collisions between moving particles to generate heat as the mass of nuclear fuel decreases. Compared with the combustion processes of fossil-fueled plants, the nuclear plant has significant advantages: less fuel and waste handling equipment are needed; only a small amount of effluent is discharged to the atmosphere; the plant can be designed for more aesthetic value—even built underground or offshore; and fuel supply interruptions are improbable since a year's supply is contained in the reactor (Benedict, 1971). However, the toxicity of nuclear wastes and increased cooling water requirements due to lower plant efficiency are two major disadvantages.

Several kinds of fission reactors are in use or under development. Most of the reactors in operation or on order use water as the core coolant. The pressurized water reactor (PWR) circulates water, pressurized to about 2,250 psi, through the reactor core and to a heat exchanger where steam is produced in an isolated steam turbine cycle. The boiling water reactor (BWR) generates steam directly in the reactor core for the steam cycle. Steam temperatures for both units have been about 500°F, but newer installations are closer to 700°F. The overall steam cycle efficiency in PWR and BWR plants is approximately 33 percent, which means that they require substantially more cooling water than a 40 percent efficient coal-fired plant of the same size.

A new type of reactor, the high temperature gas-cooled reactor (HTGR), is being scaled up to much larger commercial sizes. A 40-Mw HTGR was built in 1967, a 330-Mw plant is nearing completion, and two plants over 1,000 Mw are in the advanced design stage. The HTGR uses graphite to moderate the neutrons and helium gas to function as the coolant. The helium reaches 1,400°F passing through the core and produces 1,000°F steam in a heat exchanger. This reactor has an efficiency of about 40 percent (Federal Power Commission, 1971).

All of these fission reactors use as fuel the fissionable uranium-235 which is less than one percent of natural uranium. Known and projected uranium resources in this country are limited. Like other resources, they are composed of high grade ores that are relatively inexpensive to obtain and lower grade, more expensive reserves. Some experts estimate that the low cost ores could be exhausted in 30 years, resulting in higher uranium prices and higher costs for producing electricity (Benedict, 1971). The major developmental program for breeder reactors, discussed below, is in response to the resource problem.

### **Experimental Methods**

Many new methods for converting energy resources to electric power are being proposed due to the rapidly increasing demands on limited traditional fuels and other resources. Some of these technologies hold great promise as methods for utilizing unlimited energy resources; others are of interest due to their potentially high conversion efficiencies, versatility or other factors. A brief recapitulation of the essential characteristics of the more prominent experimental technologies will indicate where future progress in energy technology may occur. The availability of funds for R&D and, subsequently, the capitalization of operating units will control the widespread use of these or other new technologies. While the calculations for a proposed method may project very attractive values for one or two important parameters, such as efficiency, a realistic evaluation of the method must include dependable data for all the significant parameters. Generally, these data are increasingly refined through a sequence of steps such as a detailed engineering design, component prototypes, an operational unit prototype, and scaled-up operational units.

**Breeder reactors.** The breeder reactor is expected to reduce the cost of fuel for a utility, since it produces more nuclear fuel than it consumes while generating electricity. In this reactor excess neutrons from the fission of U-235 or plutonium convert nonfissionable U-238 and thorium into fissionable plutonium and U-233, respectively (Benedict, 1971). The most important attribute of a breeder would be its ability to use the relatively abundant U-238 to produce enough nuclear fuel to supply another reactor every few years. Fissionable fuel doubling time depends on the reactor design and operation. The production of fuel would sharply reduce the consumption rate per unit of electricity generated for the relatively scarce U-235 fuel. The breeder reactor is expected to require only one percent of the amount of uranium per unit of electrical output as that required by a conventional light-water reactor. Even a tenfold increase in the price of uranium would not affect the competitiveness of the breeder *vis-a-vis* fossil fuels. It has been estimated that the unit capital cost of a fast breeder could be as much as \$50 per kilowatt higher than a light-water reactor without the breeder losing its economic advantage (Benedict, 1971).

Two types of fast neutron breeders are being considered, both of which would double their fuel supply in eight to ten years. The liquid metal fast breeder reactor (LMFBR) would use a sodium coolant for the core, where the coolant reaches 1,100°F before moving to a heat exchanger to produce steam. A program is currently underway to develop an LMFBR pilot plant that is expected to have an efficiency of 40 percent (Federal Power Commission, 1971).

The gas-cooled fast breeder reactor (GCFBR) would use helium under pressure as the coolant. The technology already developed for the HTGR fission reactor would be applicable to the GCFBR. An efficiency of 40 percent is also expected for the GCFBR (Benedict, 1971).

Several technological problems in each design are being intensely researched, and satisfactory solutions appear to be possible. A major problem with the GCFBR is the prevention of overheating in the fuel if the helium cooling system should fail. Although the LMFBR does not have this problem, refueling the reactor would be more difficult since liquid metal is opaque, and this coolant would become intensely radioactive from normal operation. The liquid metal is also highly reactive with air or water, so the steam and reactor systems must be carefully isolated. However, several versions of the LMFBR have been built and operated both here and abroad (Benedict, 1971).

One of the most challenging problems for development of breeders is the handling of plutonium fuel and disposal of radioactive wastes. Plutonium use involves substantial fire hazard, and it is very toxic. Waste disposal facilities must be prepared to accommodate millions of gallons (or dry equivalent) of radioactive materials for thousands of years.

**Fusion.** In contrast to the fission reactor process which transforms fuel elements of high atomic weight to elements of lower atomic weight and captures the lost mass energy, the fusion process combines low atomic weight nuclei to form substances with greater atomic weight. The fusion process also involves a loss of mass and the release of energy which might be converted indirectly to electricity. The ultimate fusion process, however, would generate electricity directly, requiring no intermediate conversion steps.

The fusion reaction might, for example, use two isotopes of hydrogen—deuterium and tritium (D-T). In the D-T reaction, a lithium isotope bombarded by neutrons is transformed into tritium which, in turn, is reacted with deuterium to yield helium, neutrons and energy. In generating electricity, the

neutrons would be used to produce more heat and tritium to sustain the reaction. Heat would be drawn off to power a conversion system for electricity.

In a deuterium-deuterium reaction there is also a possibility of direct generation of electricity. The basic working fluid of the reactor would be a completely ionized plasma from which electrons could be tapped to generate the desired flow of electricity.

In order to achieve a sustained fusion reaction, very high temperatures (up to 100,000,000°C) are necessary to create a plasma in which the atoms of the materials are so energetic that they are stripped of their electrons, to yield a mixture of atomic nuclei and free electrons. Such temperatures can be sustained only in an environment which prevents the reacting plasma from contacting the walls of the enclosing chamber. Magnetic fields are the only known method for containing the plasma.

The research problems for fusion are formidable, and a sustained fusion reaction is not presently possible. Achieving the high temperatures and magnetic fields are the most obvious problems, and significant advances in plasma physics will be necessary. If these problems can be solved, the world will have access to a virtually unlimited source of energy. It has been estimated that the oceans contain enough hydrogen isotopes to supply the world's energy needs for 20 billion years (Energy Study Group, 1964). In comparison to the fission reactors now being built, the fusion reaction would generate little radioactive waste and would have no potential for hazardous overheating; the reaction would merely stop if problems were encountered.

**Geothermal.** While the utilization of geothermal resources to generate electricity does not require the same order of technological advances as other experimental technologies, it is discussed in this context because it will remain a minor power source until the necessary geologic exploration and steam cycle equipment modifications are achieved. The minor importance of geothermal energy (which today accounts for only 200 Mw of electrical generating capacity in the U. S.) stems from the scarcity of places where subterranean steam under pressure has been found. Geysers and hot springs mark the locations of most known areas of geothermal potential. Only one geothermal site in the U. S., located near San Francisco, California, is used for generating electricity. Sophisticated techniques have recently been developed for locating additional geothermal resources, and exploration programs are now being conducted by corporate and government geologists.

Geothermal energy is available in localized areas where heat from the earth's mantle (20-35 miles deep) flows upward into the earth's crust or where heat is produced in the crust by friction between rock zones in relative motion. Ground water percolates downward several miles where it becomes heated, expands, and moves back toward the surface. If a layer of impervious rock prevents the water from rising far enough to dissipate the heat, a heat reservoir of hot water or steam is formed with temperatures as high as 700°F. Drilling operations have tapped these reservoirs to power steam cycle generating plants in several localities around the world (Bowen and Groh, 1971).

A geothermal plant is economically comparable to other thermal installations. Its capital cost is about 75 percent that of a fossil-fueled plant and half that of a nuclear installation—chiefly because boilers, fuel handling, and combustion equipment are not needed. However, additional heat exchangers and other equipment would be needed in many installations since the minerals dissolved in subterranean wet steam would quickly foul a steam turbine. Most geothermal sources will provide low quality steam in comparison to fossil-fueled or nuclear sources. Very little pollution control equipment or surface

water for cooling would be required for a geothermal plant, and little environmental impact has occurred at sites that have been used for up to 60 years (Bowen, 1973). Most plans for geothermal site development include some method for circulating water back to the underground zone of hot rock so that the resource is not depleted; however, the feasibility of doing this has not been demonstrated.

**Fuel cells.** Like the fusion reactor, the fuel cell generates electricity from a very abundant fuel—hydrogen. The basic principle underlying fuel cell technology has been known for a century: hydrogen and oxygen in a special environment react to produce electricity and water. Hydrogen is one of the most abundant elements, and the oceans could supply immense quantities of it for use in fuel cells if inexpensive water dissociation technology were perfected. The hydrogen/oxygen fuel cell has been a major source of electricity in spacecraft. Ground power units of up to 12.5 kilowatts (Kw) in capacity have been developed to use gaseous fossil fuels enriched with hydrogen and air. Similar fuel cells in the 50-Mw range are under development.

The advantages of the fuel cell are significant. Besides the potential abundance of hydrogen fuel, the fuel cell is more efficient than other energy converters, emits almost no pollutants, and is able to operate efficiently at partial capacity in a variety of locations. It can be "stacked" to increase capacity in accordance with need or demand for electricity and, therefore, can provide for units as small as a remote meteorological monitoring station or as large as several hundred Kw for utility applications.

The major disadvantage of the fuel cell is that the current commercial versions are relatively expensive—approximately \$350 per Kw as compared with \$125 per Kw for standard fossil steam plants. By 1980, anticipated advances in size and production capability should significantly reduce this cost difference and give fuel cells greater appeal.

**Magnetohydrodynamics.** Direct conversion of heat energy to electricity is possible with the technology of magnetohydrodynamics (MHD). A hot ionized gas or liquid metal passing through a strong magnetic field functions in the same way as the rotating copper conductors of a conventional generator to induce a flow of electricity. Several approaches are under study, including: open cycle, in which the high temperature exhaust gas could be used to generate additional steam power; closed cycle, in which an ion-seeded noble gas working fluid (e.g., argon) is recirculated; and liquid metal systems, which involve potassium or sodium as the working fluid. The open cycle's high temperatures (5,000° F) make this system a good prospect for topping unit application with steam equipment for an overall efficiency of 50-60 percent. Closed cycle MHD at 3,500° F is thought to be potentially useful as a topping system for advanced fission reactors. The liquid metal concept involves temperatures up to 2,000° F, since liquid metals are more conductive than the gases even at the lower temperatures.

Several research projects are presently dealing with MHD problems, including ways to burn coal fuels, develop high temperature electrodes and superconducting magnets, remove nitrogen oxides from stack gases, and improve anti-corrosive structural materials (Federal Power Commission, 1971).

**Solar energy.** Most of the earth's energy is derived from the sun, and reflection on this fact has prompted men to seek ways to use the sun's energy in a more direct fashion. One proposed system would collect and store solar energy for conversion to electricity at 30 percent efficiency. New sunlight absorbing coatings would take up heat, store it in molten salt reservoirs, and pass it through a heat exchanger at 1,000° F for a steam cycle. It is estimated that about 5.5 square miles of Western desert would hold enough collectors to run a 1,000-Mw electric plant. Current estimates put the capital cost at

\$1.1 billion, and electricity would be produced for 40 years at an average cost of a half cent per Kwhr (Meinel and Meinel, 1971).

The concept of an orbiting space station to collect radiant energy and convert it to electricity for transmission to earth by microwaves is also under consideration. A 10,000-Mw station would require a five-square-mile panel in orbit and a six-square-mile receiving area on the ground. It would cost about twice as much as a nuclear fission plant. An estimated 125 such stations would meet the increase in demand for electricity that is projected for the 1990-2000 decade (Summers, 1971).

The Federal Power Commission has judged that such solar energy systems would involve excessive costs at the present time. Too many questions also remain concerning long-term (30 years) reliability and possible harmful environmental effects to make them immediately attractive as energy generation techniques (Federal Power Commission, 1971).

Several other technologies are being considered in scientific circles—e.g., electrogasdynamics, thermionics, thermoelectric generation, wind power and tidal power. They have not been discussed here because they appear at this time to be very remote possibilities for supplying large amounts of electricity. In order to concentrate on generation technologies, the problems and important technological advances in electricity transmission and distribution have also been omitted. For the purposes of this study, sufficient perspective for an examination of aerospace contributions to the electric power industry can be obtained by concentrating on power generation alone.

**ATTACHMENT II**  
**OVERVIEW OF LEWIS RESEARCH CENTER ACTIVITY**  
**IN ELECTRIC POWER GENERATION TECHNOLOGY**

The Lewis Research Center, currently the third largest of NASA's ten centers, has had a major program responsibility for research and advanced technology in propulsion and power systems for flight. Since 1941, the center has made fundamental contributions to the same basic technologies that are used in the electric power industry's standard energy conversion equipment. Many of the proposed new electric generating methods, such as closed Brayton cycles, binary cycles, combined cycles, and solar systems, will also depend on the technological areas which have been extended by the Lewis effort. Broad-based technological programs to solve major energy conversion system problems have been conducted at Lewis through an integrated interdisciplinary approach which includes in-house research, contracted industrial development and professional activity. Testing and test results occupy a key role in this cooperative effort, together with systems analysis, design, fabrication and basic materials research.

At present, Lewis employs about 1,700 scientists and engineers. The facilities, which represent an original investment of over \$250 million, include sophisticated equipment for testing materials, designing components, and operating energy conversion units such as combustors, boilers and turbomachinery. All of the major test facilities and laboratories are provided with modern data handling equipment which is integrated with the center's digital computer systems.

This attachment presents a brief overview of the energy conversion technology developed at Lewis in the areas of physical sciences, materials, gas turbines, and space power and propulsion systems.

**Physical Sciences**

In the past 20 years, Lewis researchers have investigated a wide range of properties related to the chemical thermodynamics of combustion and detonation. This involved extensive work in chemical equilibria, kinetics and reaction rates. For example, the combustion reaction rates of carbon monoxide with hydrogen were studied for several years to develop an accurate prediction of the reaction rates for methane combustion. As a part of this effort to predict the behavior of high temperature gases during expansion, thermodynamic data and computer analysis techniques were developed as a means of evaluating future chemical rocket performance.

Plasma research at the center is directed toward understanding plasma behavior in useful ranges of density, temperature, and magnetic field strengths for rocket propulsion and electric power generation. Among the plasma processes under experimental or theoretical investigation are fusion and closed loop magnetohydrodynamics (MHD). The Lewis superconducting magnet facility, which was started in 1964, was the first of its kind to be used in plasma physics or fusion research. Over 500 experimental runs have been successfully completed at the facility. The MHD generator, installed in 1968, is used to study power generation with nonequilibrium ionization using a cesium seeded argon plasma. The concept of using a high temperature gas-cooled reactor, a turbine-driven compressor, and an MHD generator to produce electric power in space has also been theoretically investigated.

Superconductor research at Lewis has been concerned mainly with the development of more economical superconductors, fabrication methods for superconducting devices, stabilization techniques under large-scale operating conditions, and a better theoretical understanding of superconductivity. The

laboratory's superconducting magnets include the largest and strongest such units in the world. Conductor and magnet stabilization studies, flux flow and mapping experiments, and experiments on strong-coupling and nonphonon superconductors have been completed at the facility.

Fluid mechanics problem areas such as change of phase, near critical fluids, and cooling capabilities of cryogenic fluids have been studied at Lewis for a variety of space propulsion and power applications. Some of the specific studies in phase change are: fundamentals of boiling mechanisms; heat transfer to a fluid near its critical point; stability of vapor-liquid interface spanning a pipe; and choked flow in a two-phase medium. Mathematical models were developed at Lewis to predict the fluid behavior and heat transfer for flow through a nozzle. Lewis has been working jointly with the National Bureau of Standards to develop a generalized computer program that provides basic property data on nine common gases and some hydrocarbons for engineering applications.

Experimental and theoretical studies in nuclear reactor physics have been conducted at the center to improve the accuracy of reaction calculations used primarily to perform better shielding calculations for space nuclear power systems. Research was undertaken at the center's 60-megawatt(t) Plum Brook Reactor Station to determine the effect of nuclear radiation on selected materials. In another development, statistical studies were used to obtain a new method for calculating the variation of neutron capture cross section with energy for fast neutrons, and the method has been applied to reactor stability design studies at Lewis.

### **Materials**

Lewis Research Center has established profoundly important relationships between bench-scale test results and the performance of materials in engineering applications. This understanding of materials science is based on tens of thousands of fatigue, creep-rupture, and fracture toughness tests conducted at the center with hundreds of ferrous and nonferrous alloys. The center's fatigue research facility, with its advanced equipment, is considered to be one of the most versatile in the country. Test equipment is available for fatigue testing from  $-452^{\circ}\text{F}$  to  $2,200^{\circ}\text{F}$ , creep-rupture testing up to  $5,500^{\circ}\text{F}$  with vacuum capability to  $10^{-7}$  Torr, and tensile strength testing to 1.2 million pounds. A staff of 23 professionals is directly associated with the effort to analyze mechanical properties of alloys. In the last 30 years, this research effort has produced a number of significant advances in the technology.

A widely used method for analyzing stresses in turbine disks was developed at Lewis. Also, the first strain gages for applications above  $1,000^{\circ}\text{F}$  originated at this facility. The basic relationship between plasticity and low cycle fatigue, methods for assessing creep-fatigue damage in metal components, extrapolation techniques for creep-rupture data, fracture toughness testing procedures, and techniques for the elasto-plastic analysis of flawed components were produced by the center's research activity.

A number of new or improved materials and processes were also developed by the long-term materials research effort at Lewis. Included in these advances for high-temperature or irradiated applications, such as gas turbines and space nuclear power plants, were: super, refractory, and composite alloys; protective coatings; dispersion hardened metals; grain oriented casting; and powder metallurgy. In addition, contracted and in house research by Lewis has provided basic design data, advances in the metallurgical analysis, and a better understanding of corrosion phenomena for various alloys.

## Gas Turbines

Gas turbines have been studied at Lewis since the early days of jet aircraft engines. Test data, analytic studies, and designs for increased efficiency and reduced air polluting emissions were generated for gas turbine combustion and combustors as part of this effort. The center has contributed to the evolution of combustor designs and currently manages the Clean Combustors Program in which several combustor designs are being evaluated by industrial contractors. Alternative gas turbine fuels, such as natural gas and hydrogen, have also been investigated at the center. In particular, the technology pertinent to liquid hydrogen and other cryogenics—i.e., large storage vessels, tankcars and trucks, lines, valves, pumps, vents, and insulation—has been advanced by Lewis and its program contractors.

Lewis conducted much of the early research on the gas turbine blade and stator cooling methods which permit higher turbine inlet temperatures and, therefore, higher turbine efficiencies. Testing facilities, cooling techniques, component fabrication processes, computer design methods, and heat transfer analyses were developed at the center. This research continues to advance technical capabilities in turbine cooling. The current effort is directed toward achieving an inlet temperature of 4,000° F.

Turbine blading, fans, and compressors have been investigated for many years at Lewis, and numerous computer programs for analyzing flow dynamics were developed. Tandem blade configurations, higher blade loading designs, and flow distortions have been studied, both experimentally and analytically at the center. Problems encountered at compressor pressure ratios between 30 and 40, with turbine inlet temperatures above 3,000° F, are now being investigated.

Bearings research at Lewis, particularly for high temperature gas turbine applications, has produced test data and analyses for hundreds of rolling and fluid film bearings and tens of thousands of bearing components. Since 1950, an average annual staff of ten professionals has made this one of the largest such efforts in the western world. The testing and analysis program for thousands of seal materials and designs, lubricants, and lubricating methods has had an average annual professional staff of 15 for over 30 years. It has created solutions to many practical problems as well as a basic understanding of the subject. This is the longest, continuously sustained program of its type known to exist in the world. High speed shafting and gearing are two other areas of significant research activity at the center.

Two other important areas of gas turbine research at Lewis are noise reduction and turbine control systems. Design and analytic studies have been conducted in each area. Preliminary results from the Quiet Engine Program, for example, indicate that a jet engine will soon create about as much noise as a busy metropolitan street.

## Space Power and Propulsion Systems

Components and their performance in liquid metal (mercury and potassium) Rankine cycle electric power generating systems have been extensively investigated for space nuclear power applications at Lewis and under Lewis contract management. Components (boilers, turbines, condensers, valves, and pumps) for mercury and potassium power systems have each been tested for 10,000 hours or more. Most of the potassium test runs were at temperatures between 1,500° F and 2,200° F. Also, a complete mercury power system was successfully operated for more than 7,000 hours.

A program to develop closed-cycle gas turbine electric generating systems for space power with nuclear reactor or isotope heat sources has also been underway at Lewis. Testing of such a unit for more than 10,000 hours has demonstrated that it has a long life and high efficiency.

Several advanced nuclear reactor designs were investigated by Lewis scientists in conjunction with the Atomic Energy Commission. A uranium-zirconium hydride (ZrH) reactor was under development to generate electric power in space with either a closed-cycle gas turbine or a thermoelectric conversion system. The center also conducted in-pile fuel and materials testing, fast spectrum neutronics experiments, and materials investigations to develop a compact fast spectrum reactor which was to be coupled with a closed-cycle gas turbine generating system for manned orbiting station power generation. The gas and solid core reactor research programs were directed toward nuclear rocket propulsion applications. In addition, Lewis research related to the gas core reactor included studies and experiments in fluid mechanics, gaseous radiant heat transfer and reactor neutronics.

The Lewis research program in thermionic and thermoelectric conversion systems included studies of electronic, energetic, mass, and nucleonic transport and interactions. Computer-supported cesium diode performance studies were conducted at the center and under Lewis contract management to provide key information for developing nuclear reactor thermionic systems. These systems could provide for direct generation of electric current in the reactor core.

Some of the earliest feasibility studies for solar cell, fuel cell, and battery technology were conducted at Lewis or were done under contract to the center. These units have become the conventional space power systems. Improved materials, fabrication processes, and performance analyses for these units have also been developed at the center.

### **Conclusion**

The extent of Lewis Research Center activity in electric power generation technology was only briefly described in this attachment. The relevant technologies developed at the center or under its contract management represent one of the broadest achievements in the field for any single, American institution. The industrial application of these technologies is now becoming significant for early Lewis results (see Attachment IV).

The center's research activity in power systems technology occupies a ground breaking role by performing the preliminary evaluation of new design concepts and supporting initial feasibility studies. For example, the current work on gas turbine components is directed toward operating temperatures above those for any operational or prototype turbine engine. As in the past, one may expect applications first in military aircraft, then in commercial aircraft, and, finally, in ground power units. Cost and operating experience are crucial factors in this sequence; however, it is important to understand that efficiency increases for ground power turbines depend on operating condition increases. The projected efficiencies of over 50 percent for combined (gas and steam turbine) cycle power generating plants is based on the assumption that the gas turbine operating conditions currently being investigated at Lewis will become economically feasible in the future.

**ATTACHMENT III**  
**NASA PUBLICATIONS RELEVANT TO THE ELECTRIC POWER INDUSTRY**

The variety of NASA publications in nine of the technologies that are relevant to the electric power industry is illustrated in the following list of titles. The list includes: Tech Briefs (B), Contractor Reports (CR), Technical Memoranda (TM), Technical Notes (TN), Technical Reports (TR) and Special Publications (SP).

**THERMODYNAMICS**

- |           |  |
|-----------|--|
| B67-10329 | "Computer Program Resolves Radiative, Conductive, and Convective Heat Transfer Problems for Variety of Geometries"   |
| B70-10094 | "Atmospheric Composition Affects Heat- and Mass-Transfer Processes"  |
| B71-10272 | "Compressed Gas Handbook"  |
| CR-924    | "Two-Stage Potassium Test Turbine"   |
| CR-96468  | "A Survey of the Thermodynamic Properties of the Compounds in the Element CHNOPS"  |
| TR-R-67   | "Propellant Vaporization as a Design Criterion For Rocket-Engine Combustion Chambers"  |
| SP-273    | "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance Incident and Reflected Shocks, and Chapman-Jouguet Detonations" |

**COMBUSTION**

- |            |   |
|------------|---|
| B67-10455  | "A Method of Determining Combustion Gas Flow"   |
| B69-10711  | "Properties of Air and Combustion Products of Fuels with Air"   |
| B70-10652  | "Controlled Droplet Spray Generator"  |
| CR-920     | "Combustion Instability Prediction Using a Nonlinear Bipropellant Vaporization Model"   |
| TM-X-2216  | "Effects of Various Diffuser Designs on the Performance of an Experimental Combustor Insensitive to Radial Distortion of Inlet Airflow" |
| TM-X-52334 | "Liquid Rocket Combustion—An Aerodynamically Controlled Process"  |
| SP-194     | "Liquid Propellant Rocket Combustion Instability"   |

**FLOW DYNAMICS**

- |            |  |
|------------|--|
| B66-10228  | "Studies Reveal Effects of Pipe Bends on Fluid Flow Cavitation"  |
| B69-10772  | "Surface-Renewal Models for Heat-Transfer Between Walls and Fluidized Beds"  |
| B71-10392  | "Computer Program/TURBLE/for Calculating Velocities and Streamlines in Turbomachines"                                    |
| CR-102820  | "Analyses for the Description of Rocket and Airbreathing Propulsion System Combustion Chamber and Nozzle Flows"          |
| CR-110777  | "Flow Excursions in a Simulated Gas-Cooled Reactor Passage"  |
| TM-X-52655 | "Behavior of a Vapor Bubble in a Pulsating Pressure Field"   |
| TN-D-4498  | "Analysis of Pressure-Drop Function in Rankine Space Power Boilers With Discussion of Flow Maldistribution Implications" |

### MATERIAL PROPERTIES

B68-10046	"Survey of Fracture Toughness Test Methods"
B69-10147	"Torsion System for Creep Testing with Multiple Stress Reversals"
B69-10372	"Effects of Hydrogen on Metals"
B71-10099	"Ultrasonic Metal Etching for Metallographic Analysis"
CR-72714	"Evaluation of Coatings for Cobalt- and Nickel-Base Superalloys"
CR-72682	"Crack Initiation at Notches in Low Cycle Fatigue"
CR-61631	"A Method for Correlating Elevated Temperature Fatigue Data"
TM-X-68023	"Temperature Effects on the Strainrange Partitioning Approach for Creep-Fatigue Analysis"
SP-131	"Potassium Rankine System Materials Technology"

### METAL FABRICATION

B69-10264	"Welding, Brazing, and Soldering Handbook"
B69-10471	"A Biaxial Weld Strength Prediction Method"
B71-10028	"Method for Joining Metals of Significantly Different Expansion Rates"
CR-61463	"Out-of-Vacuum Electron Beam Welding"
TM-X-61300	"Analysis of Thermal Stresses and Metal Movement During Welding"
SP-5062	"High-Velocity Metalworking"

### BEARINGS, LUBRICANTS, AND SEALS

B66-10373	"Bearing Alloys with Hexagonal Crystal Structures Provide Improved Friction and Wear Characteristics"
B68-10261	"Dynamic-Reservoir Lubricating Device"
B68-10270	"Spiral-Grooved Shaft Seals Substantially Reduce Leakage and Wear"
CR-1549	"Transient Journal Bearing Analysis"
TM-X-1958	"Comparison of Experimental and Ideal Leakage Flows Through Labyrinth Seals for Very Small Pressure Differences"
TM-X-52426	"Various Modes of Wear and Their Controlling Factors"
SP-38	"Advanced Bearing Technology"

### ENGINEERING DESIGN

B67-10261	"Analytical Technique Permits Comparison of Reliability of Alternative Mechanical Designs"
B70-10487	"Quick Computational Method for Fluid Flow Through Duct System"
B71-10038	"FEATS—Finite Element Thermal Stress Analysis of Plane or Axisymmetric Solids"
CR-93924	"Zero Leakage Design for Ducts and Tube Connections for Deep Space Travel. Volume 5: Tube Connector Design Principles and Evaluation"
CR-109646	"Seals Design Guide: Study of Dynamic and Static Seals for Liquid Rocket Engines"
SP-5039	"Structural Design Concepts"

### RELIABILITY AND QUALITY ASSURANCE

- B66-10405 "Design Reliability Goal Developed from Small Sample"  
 B67-10430 "Study Made of Acoustical Monitoring for Mechanical Checkout"  
 B71-10194 "Predicting Service Life Margins"  
 CR-61952 "Development of the Ultrasonic Delta Technique for Aluminum Welds and Materials"  
 TM-X-52790 "An Approach to Reliability Determination of a Rotating Component Subjected to Complex Fatigue"  
 TM-X-61123 "Problems of Increasing the Reliability of Automatic Mining Equipment"  
 SP-5082 "Nondestructive Testing: Trends and Techniques"

### CONTROL TECHNOLOGY

- B66-10498 "Quick-Response Servo Amplifies Small Hydraulic Pressure Differences"  
 B68-10234 "Design Techniques--Stochastic Controllers"  
 B69-10454 "Special Purpose Computer Provides Programmable Digital Filter for Sampled-Data Control System"  
 B70-10115 "New Procedure for Design of Self-Adaptive Control Systems"  
 CR-54005 "Feasibility Study-Application of Fluid Amplifiers to Reactor Rod Control"  
 CR-91042 "A Time-Varying Bound on Nonlinear System Transient Response"  
 CR-94421 "Lyapunov Control System Synthesis of Highly Resonant Plant"  
 TM-X-52845 "Requirements, Design, and Performance of a Control System for a Brayton Power System"

**ATTACHMENT IV**  
**SUMMARIES OF TECHNOLOGY TRANSFER EXAMPLES INVOLVING**  
**THE USE OF NASA TECHNOLOGY IN THE ELECTRIC POWER INDUSTRY**

NASA CONTRIBUTIONS	TRANSFER STAGES							
	1		2		3		4	
	Cont.	Term.*	Cont.	Term.	Cont.	Term.	Cont.	Term.
● Apollo Program Checkout and Control Computer Systems					86007**		86005	
● Automatic Synthesis Program (ASP)			84983				86006	
● Computer Program for Obtaining the Roots of Matrices with Polynomial Elements (ROMPE)					84984			
● Computer Programs to Analyze Combustion			86011		86010		86009	
			86013		86012			
			86015		86014			
					86016			
					86017			
					86018			
● Control Design for Stochastic Nonlinear Systems			67812					
● Electric Power Industry Conference	84985	84989	84986					
	84987							
	84988							
● Fracture Mechanics	85203		85201	12475	85204			
			85206		85208			
			85211		85212			
			85214		86001			
● Fuel Cells							84992	
● Fuel Vaporization Model			87030				87029	
● Gas Turbine Cooling Technology							90556	
● Heat Pipe Applications			84982		86008		83601	
● High Temperature Fatigue Analysis			85213		85202			
			85307		85205			
			86002		85207			
					86000			
					14155			
● Improved Method to Determine Thickness of Radiation Shields								
● Liquid Impact Erosion Model					84980			
● Manson-Haferd Time-Temperature Parameter			85210		85209			
● NASTRAN					84977		84981	
							86003	
● Nuclear and Atomic Physics Handbook	45706		45928		34992			
					45742			
					46785			
● Potassium Rankine Cycle Test Program			86004					
● Reliability and Quality Assurance for NASA Programs			87032		84978		84976	
					84979			
					87031			
					87033			
● Rocket Engine Steam Generator			84990		84991			

\* The action status, continuing or terminated, of transfer cases at the time DRI-TRIS contacted users. Cases are classed as terminated when (a) no further adaptation or adoption is contemplated, (b) a better technical alternative has been found, or (c) continued transfer activity is not economically feasible.

\*\*Numbers in columns refer to TRIS case numbers.

Preceding page blank

**ATTACHMENT IV**

**Summaries of Technology Transfer Examples Involving  
the Use of NASA Technology in the Electric Power Industry**

## APOLLO PROGRAM CHECKOUT AND CONTROL COMPUTER SYSTEMS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The Apollo program requirements for computer checkout and control systems caused major advances in computer systems technology. Some of these advances are being used in the development of a new generation of digital computer monitor and control systems for electric power transmission grids. Four Apollo program innovations and their current applications are briefly described in this summary: the Apollo Guidance Computer Executive program; Lunar Module Guidance Computer targeting programs; the automatic checkout system for Apollo; and digital color television computer displays for the Mission Control Center at the Manned Spacecraft Center.

The Apollo Guidance Computer (AGC) was designed in the early 1960's at the Massachusetts Institute of Technology, under contract to the Manned Spacecraft Center, to be incorporated into the Guidance and Navigation Systems in the Command and Lunar Excursion Modules. In 1966 the AGC was quite representative of the state-of-the-art in guidance computers. It was designed to employ three standard programs: the Interpreter program, which allows efficient expression of double precision matrix programs for navigation, attitude control, and steering; the Executive program, which allots computer time among various jobs according to a priority schedule; and the Waitlist program, which provides interrupted entry to other programs at specified intervals of real time.

TRW Systems in Houston, Texas conducted the preflight testing of the AGC, under a Manned Spacecraft Center service contract, and verified that it met the mission profile requirements. During the course of this work, TRW computer experts became familiar with the Executive program and its real-time priority scheduling capabilities.

Since 1970, approximately 25 TRW Systems computer experts have been under subcontract to TRW Controls, a major producer of automatic computer controls in Houston (86005), to develop real-time programs for electric power dispatch computers. TRW Controls has installed more than 200 computer control systems in petroleum processing, pipelines, and the electric power industry since 1954. The TRW Executive program, which was developed from the AGC Executive, is now standard in the company's larger monitoring and control systems. The first of these systems was installed for the General Public Utilities Corporation, which serves 1,300,000 residential, commercial, and industrial customers in a 25,000-square mile area in Pennsylvania and New Jersey. Three more of the systems have been installed or are on order.

The TRW Executive program extends the real-time control capabilities of commercially available software for monitoring and control. Circuit breakers and small changes in generator output and frequency can be automatically controlled through the TRW unit with a two-second response time. In addition to the Executive program, the new TRW control system includes state estimation programs for economic dispatch. These were adapted from similar programs developed at TRW Systems for the Manned Spacecraft Center to calculate targeting routines in the Lunar Module Abort Guidance Computer.

The automatic checkout equipment for the Apollo spacecraft, ACE-S/C, is one of the most complex computer systems in the world. It was used to integrate the extensive Apollo checkout procedures conducted at Marshall Space Flight Center, Grumman Corporation, Kennedy Space Center, Manned Spacecraft Center, and North American Rockwell Corporation from manufacture to launch. One

of the most important problems in the development of ACE-S/C concerned the reliability of the human/computer interface. This was resolved by a master program which translated between operational computer programs and the input/output display equipment used by human operators. North American Rockwell, the Apollo spacecraft manufacturer, designed and implemented information systems that integrated Apollo checkout subsystems into ACE-S/C. The corporation subsequently formed a new division, North American Rockwell Information Systems Company (NARISCO) in Anaheim, California (86006), to develop commercial products with the expertise in systems development, design, and management that the corporation had obtained during the space program.

Later, NARISCO acquired the Philco-Ford Corporation's product group that had developed a new digital color television display system for the Mission Control Center. The digital display was a major advance in human/computer interface technology, since it provided significant improvements in accuracy, content, versatility and control capabilities. The Philco-Ford product group had adapted this display technology to electric transmission monitoring and control systems before it became part of NARISCO. Some of the earlier installations were at the Houston Lighting and Power Company, the Cleveland Electric Illuminating Company, and the Pennsylvania-New Jersey-Maryland power pool system. NARISCO is currently improving the producibility of the digital display system hardware.

In 1969 NARISCO received a contract from the Philadelphia Electric Company in Pennsylvania (86007) to develop and install an advanced real-time control system for the company's network of generating stations and distribution equipment. NARISCO experts adapted computer systems technology from the ACE-S/C system and other sources to create the new Philadelphia Electric control system, which is currently undergoing final acceptance tests. Two specific technologies adapted to this application were the master program translator and the digital color television display system. A spokesman for Philadelphia Electric stated that the company's previous network supervisory system did not provide operator interface capability or direct interconnection of several different generating plant control computers. As a result, the control center operators could not monitor the more than 3,000 items of power system condition information received every 30 seconds, and there was no feedback control of generating plant output. The NARISCO system provides a solution to each of these problems.

General Public Utilities Corporation and Philadelphia Electric Company are members of the Pennsylvania-New Jersey-Maryland power pool system (PJM). They represent approximately one-half of the pool's 20,000 megawatts of generating capacity. The PJM dispatch computer sends a continuous basic input signal to each member company that sets the changing level of generating load for that company. In real time, the company control center computer dispatches a load request to each generating plant, matches the frequency of each plant's output current to the fixed pool frequency, and stabilizes the company's transmission system after severe disturbances such as equipment failure. The advanced computer systems described in this summary are being installed to minimize system failures, such as the 1965 Northeast Blackout, and to ensure the safest, most economical operation of generating plants as the demand for electricity fluctuates.

#### **Control Numbers**

Tech Brief Number: None  
 NASA Center: Manned Spacecraft Center  
 TRIS Case Numbers: 86005, 86006, 86007  
 TEF Number: 465  
 Date of Latest Information Used: February 1, 1973

## AUTOMATIC SYNTHESIS PROGRAM (ASP) TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The Automatic Synthesis Program (ASP) was developed between 1963 and 1966 at Martin-Marietta Corporation in Baltimore, Maryland, under contract to the Ames Research Center. One of the principal investigators, R. E. Kalman, played a central role in the development of optimal control theory; and ASP was created to be an efficient analytic design tool for control systems, including optimization of linear dynamic systems. It has been successfully used on several reentry and lunar landing control problems, aircraft control, and control of large flexible booster rockets. Both the program and the user's manual, NASA CR-475, are designed to be easily understood and used by anyone with a background in modern system theory, including the novice in optimal control theory. Concrete examples and mathematical derivations are supplied in the manual so that it can be used as a textbook on optimal control design. The program is available in Fortran language from the NASA-sponsored Computer Software Management and Information Center (COSMIC) at the University of Georgia.

ASP consists of an executive program and some thirty subroutines which can be conveniently used to solve most, if not all, linear problems encountered in the application of system theory. The subroutines are sufficient to solve the most general optimization problems for the standard formulation of linear dynamic system models. Many nonlinear models also may be solved by either first using the mathematical technique of linearization or the iterative use of the subroutines to approximate the actual solution.

By solving the control design problem, a control function, or law, can be obtained for the modeled system which gives the best system control strategy based on the known system dynamics and performance index. No prior assumptions are made that would determine the actual controller structure. Previous control design techniques required the control engineer to select first the controller structure and then try to get the best available performance by selecting controller settings (the system parameters). With ASP, the optimal control law is obtained by using the Riccati Equation subroutine to solve a matrix differential equation of the Riccati type. Since this solution combines the mathematical system model and the performance index equation, it is the key element in determining the control function.

Control researchers at Drexel University in Philadelphia, Pennsylvania and the Philadelphia Electric Company (84983) have developed one of the first applications for linear optimal control theory to boiler-turbine-generator control design and analysis. A nonlinear mathematical model of the most common type of fossil-fueled steam generator plant was created for this purpose and extensively verified by tests. The model was then linearized, and the Riccati Equation subroutine from ASP was programmed to solve for the control law. Simulation tests have been conducted to compare the proposed new control strategy with the existing control structure in a 200-megawatt plant, and improved performance was demonstrated. The new strategy will produce controller action which guarantees zero steady-state errors.

The exact operating conditions in the target plant are being defined to determine what degree of performance improvement can be realized. This is preparatory to implementing the control strategy in an actual, direct digital control application. Eventually, the target plant will be automatically controlled to follow the load requested by a power grid dispatch computer, if the developmental steps produce satisfactory results.

**Control Numbers**

Tech Brief Number: None  
NASA Center: Ames Research Center  
TRIS Case Number: 84983  
TEF Number: 445  
Date of Latest Information Used: January 1, 1973

**COMPUTER PROGRAM FOR OBTAINING THE ROOTS  
OF MATRICES WITH POLYNOMIAL ELEMENTS (ROMPE)  
TECHNOLOGY TRANSFER EXAMPLE SUMMARY**

The Convair Division of General Dynamics Corporation developed the Atlas-Centaur rocket under contract to the Lewis Research Center. Control designers at Convair used the Root-Locus method in designing the rocket's guidance control system. This method is based on calculating, by computer, the roots of a matrix associated with a mathematical model of the rocket. The calculations, or root loci, allow the designer to select values for system parameters which, with the given controller hardware system, will produce a desired control system quality. In 1966 Convair designers wrote an improved computer program, entitled "Roots of Matrices with Polynomial Elements" (ROMPE), that increased the speed of these calculations by an order of magnitude. ROMPE was based on a solution method for linearizing the polynomial elements that was created at the Boeing Company under an Air Force contract for B-52 control design work.

One of the Convair control engineers later joined the Control Systems Analysis Section of Gulf General Atomic Corporation in San Diego, California (84984). The engineer made minor adaptations in ROMPE so that it could be used to design the control system hardware for Gulf's high temperature gas-cooled reactors (HTGR). This version of ROMPE was applied in the control system design for the 300-megawatt HTGR under construction near Platteville, Colorado. It is currently being used in the company's development of 1,000-megawatt HTGR plants. A company spokesman reported that better reactor control system quality could be achieved for less computer time by using the modified ROMPE.

**Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Number: 84984  
TEF Number: 446  
Date of Latest Information Used: November 16, 1972

## COMPUTER PROGRAMS TO ANALYZE COMBUSTION TECHNOLOGY TRANSFER EXAMPLE SUMMARY

During the last 20 years government-sponsored research in combustion related to rocket propulsion has produced an extensive body of useful combustion technology. The Lewis Research Center played a prominent role in this effort from the beginning, and other NASA facilities participated through the 1960's. A very important type of NASA contribution to combustion technology has been the development of general computer programs to perform thermodynamic analyses of the combustion process. These programs fall into two general classes: equilibrium and kinetic.

A knowledge of chemical equilibrium compositions for a chemical system is basic to calculating the system's theoretical thermodynamic properties. One of the most widely used chemical equilibrium calculation programs in the United States, Chemical Equilibrium Calculations (CEC), was developed at the Lewis Research Center. After devising a practical calculation technique in the 1950's for high temperature chemical reactions with numerous products, Lewis researchers continued to update, generalize, and refine the basic CEC program. By 1971, CEC had become independent of the particular computer used; accurate with a built-in restriction from printing incorrect answers; general to the point that most chemical systems could be analyzed; and modular so that unnecessary subroutines for a particular problem could be bypassed. Constant volume, detonation, and shockwave phenomena could also be analyzed with CEC.

The wide scope of these developments exceeded the specific NASA requirements. This was done, in part, as a "community service" so that expanding computer capabilities could be utilized in equilibrium calculations by a large industrial community of interest. The basic thermodynamic data used as input to CEC can be obtained for over 500 chemical species from Lewis or generated by the user with another program (PAC-II) developed at Lewis. NASA announced the availability of the CEC program in Tech Brief 68-10025 and, in 1971, distributed a Special Publication (SP-273) which presented the program documentation along with several topics of general interest for chemical equilibrium analysis.

Chemical kinetic programs are used to analyze the performance of different combustor geometries and combusting techniques by calculating the exhaust gas expansion characteristics. Several important chemical kinetic programs were developed for NASA rocket research at TRW Systems, under contract to the Manned Spacecraft Center, and at the Lewis Research Center. The programs developed at TRW have been announced in four Tech Briefs: 68-10374, 68-10375, 68-10376 and 68-10377. These programs calculate the expansion of combustion produced gaseous mixtures, including condensed products, for different fuel compositions, combustion temperatures, relaxation rates and nozzle geometries. The calculation method (second order implicit integration) permits computation times that are more than two orders of magnitude less than standard explicit methods. These programs were subsequently standardized and refined for the Intragency Chemical Rocket Propulsion Group to provide a one-dimensional and a two-dimensional chemical kinetics program.

In addition to the specific programs described above, combustion research was conducted for NASA by other in-house, commercial and interagency government groups. In 1970 several researchers involved in these efforts, including the principal investigator from TRW Systems, formed a new company KVB Engineering, Incorporated in Tustin, California (86009). Since then, KVB has become a major combustion consulting firm for the electric power industry.

**Preceding page blank**

The kinetics and CEC programs are routinely used by KVB to analyze alternative fossil-fueled combustion techniques such as delayed mixing, premixed off-stoichiometric flames, off-stoichiometric diffusion flames (secondary combustion) and flame temperature control. This analysis predicts where oxides of nitrogen ( $\text{NO}_x$ ) will be formed in the combustion chamber, identifies what mechanisms are involved, and describes the affect of change in combustion techniques for the specific chamber being analyzed. The results are used as a guide in selecting new operating procedures for burners so that the production of  $\text{NO}_x$  is minimized. This method has been used to reduce  $\text{NO}_x$  emissions from fossil-fired power plants by 40 to 70 percent. It is considerably less expensive than other proposed methods, such as catalytic or electrolytic reduction. Several electric utilities and equipment manufacturers have utilized the KVB consulting service in their efforts to comply with stringent  $\text{NO}_x$  emission standards.  $\text{NO}_x$  is an important component of photochemical smog, and its production in the combustion process is primarily a function of flame temperature.

The Southern California Edison Company in Los Angeles (86010) was the first utility to use the KVB service. The company has reduced  $\text{NO}_x$  emission by 50 to 70 percent in each of its 22 natural gas-fired boilers through the use of two combustion techniques from KBV: exhaust gas recirculation and secondary combustion. These reductions were achieved without degradation of plant operation, efficiency or safety. Eight oil-fired boilers are also being converted to use the two techniques. The company will be in compliance with the Los Angeles County air pollution standards long before the 1975 deadline as a result of these modifications.

Construction of the Scattergood Steam Plant Unit 3 by the Los Angeles City Department of Water and Power (86018) was allowed to proceed solely on the basis of the low  $\text{NO}_x$  combustion techniques devised by KVB. The department had spent \$6.5 million on construction and signed contracts totaling \$24 million for equipment when a construction permit was denied on the basis of anticipated  $\text{NO}_x$  emissions of about 1,600 pounds per hour. After losing an appeal to a state court, the department was granted the permit when it agreed to operating changes that would ensure the plant's compliance with the new Los Angeles County air pollution standard limiting  $\text{NO}_x$  emissions to 140 pounds per hour. This plant is the first to be constructed under the new law, and department officials did not believe they could meet the 140-pound limit prior to the work done by KVB. The additional pollution control equipment will cost \$2 million, as compared to the total plant cost of \$68 million. Scattergood Unit 3 is scheduled to start producing almost 10 percent of Los Angeles' electricity in 1974. Most of the department's other 17 boilers are being converted to use the same techniques before the 1975 deadline.

The Public Service Company of New Mexico in Albuquerque (86013) has experimented with the techniques designed for the company by KVB.  $\text{NO}_x$  was reduced by more than 50 percent, and efficiency was increased in the trial plant. The techniques will probably be used in the company's plants in order to meet the New Mexico air pollution standards which will take effect in 1974.

Consolidated Edison Company of New York, Incorporated (86011) contracted with KVB to provide test supervision, analysis, and personnel training for the company's program to reduce  $\text{NO}_x$  emissions from its fossil-fueled steam and gas turbine plants. The company is testing KVB's combustion techniques in two medium-sized boilers, and the results appear to be favorable.

The Houston Lighting and Power Company in Texas (86012) has initiated a program to convert all 26 of its gas-fired boilers to use the secondary combustion technique designed for the company by KVB. Test programs on the Houston units have achieved  $\text{NO}_x$  reductions between 40 and 70 percent,

with no increase in operating costs. Houston Lighting and Power will receive the first innovative air recirculation boiler designed by a major boiler manufacturer (86014) in conjunction with KVB. The boiler design represents significant advances in  $\text{NO}_x$  reduction and increased efficiency for commercially available equipment.

The Gas Turbine Products Division of the General Electric Company in Schenectady, New York (86015) is conducting experiments with the techniques devised for its industrial turbines by KVB. The division is considering potential product design modifications which will reduce  $\text{NO}_x$  emissions by more than 50 percent.

The Babcock and Wilcox Company in Barberton, Ohio (86016) obtained the CEC program from Lewis Research Center about two years ago. The company uses CEC regularly in design studies for fossil-fired boiler modifications to reduce  $\text{NO}_x$  emissions and for sulfur recovery processes for several sulfur dioxide ( $\text{SO}_2$ ) cleanup systems that are being developed for power plant exhaust gases. Babcock and Wilcox engineers analyze the operating trends for different hardware configurations with CEC so that guidelines leading to experimental design improvements are established.

The Bureau of Mines' Pittsburgh Mining and Safety Research Center in Pennsylvania (86017) obtained a version of CEC from Lewis in 1967 and, subsequently, received the 1971 version. When a research program to analyze coal mine fires and explosions was initiated at the Pittsburgh center in response to the 1969 Mine Safety Act, CEC became a crucial research tool. It is now being used on a daily basis to calculate flame temperatures, pressures, and combustion product compositions, as well as for detonation simulation. These calculated results are the input data to the Bureau's computer programs which characterize the flame or detonation propagation rate down a mine tunnel. Without the program, Bureau researchers would have to use less accurate data from expensive experiments. This research will provide the basic design information needed to manufacture automatic detectors and quenching systems for installation in underground coal mines.

#### **Control Numbers**

Tech Brief Numbers: 68-10025, 68-10374, 68-10375, 68-10376, 68-10377

NASA Centers: Lewis Research Center, Manned Spacecraft Center

TRIS Case Numbers: 86009, 86010, 86011, 86012, 86013, 86014, 86015, 86016, 86017, 86018

TEF Number: 463

Date of Latest Information Used: February 7, 1973

## CONTROL DESIGN FOR STOCHASTIC NONLINEAR SYSTEMS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

A sophisticated, new control design technique was developed at the Massachusetts Institute of Technology under contract to the Manned Spacecraft Center. The technique was derived to solve optimum control problems in space vehicle guidance and navigation systems and closed-loop process controllers.

Many control systems have characteristics that are either unknown or are highly variable, and the control designer must take this into account in order to achieve satisfactory results. The new technique, described in Tech Brief 71-10306, can handle *a priori* statistical information about the unknown parameters and does not require an artificial augmentation of the cost function as a basis for considering these unknowns. These two features provide an important improvement over two previous techniques used on this problem. The solution is obtained by expanding the cost function in a power series about a deterministic trajectory, with the assumption of linear perturbation estimation and control about that trajectory.

A major manufacturer of electric generating equipment (67812) has used the TSP in developing a new surveillance system for nuclear power plants. The development has been underway for two years, and the product will be introduced in 1975. The method given in the TSP for handling nonlinear systems was very important in creating a computer program which provides estimates of nuclear processes in the surveillance system mini-computer. The product will be used as peripheral equipment on nuclear power plants to detect abnormalities in the nuclear process, improving safety and performance control information.

### Control Numbers

Tech Brief Number: 71-10306  
NASA Center: Manned Spacecraft Center  
TRIS Case Number: 67812  
TEF Number: 442  
Date of Latest Information Used: January 5, 1973

**Preceding page blank**

## ELECTRIC POWER INDUSTRY CONFERENCE TECHNOLOGY TRANSFER EXAMPLE SUMMARY

A special technology utilization conference, entitled "Conference on Selected Technology for the Electric Power Industry," was held at the Lewis Research Center in September 1968 to acquaint the industry with some of the technology that was developed for NASA programs. The topics were selected with the advice of technical representatives from the industry, and the Edison Electric Institute assisted in selecting an audience of over 200 individuals.

Members of the Lewis staff presented specific innovations and long-term research efforts in a context of the common problems faced in NASA programs and the electric power industry. The technical topics were: nuclear reactors, Rankine cycles, Brayton cycles, reliability, automatic checkout and control, instrumentation, bearings and seals, engineering mechanics and materials, cryogenics and superconductivity, and direct energy conversion. In addition, the aerospace abstract journals and the NASA Technology Utilization Program activities were described. The conference proceedings have been published with the same title in a NASA Special Publication (SP-5057).

Several of the individuals who attended the conference were interviewed in 1972 to ascertain its general impact and identify specific consequences. Due to the extremely long lead-time of six to eight years for constructing new power plants, together with the time requirements for adapting technology to a new application, no examples were found in the advanced stages of transfer. However, the role of the conference in expanding the perspective of industry representatives and their continued interest in the specific technologies should not be underestimated. Five examples are given below to illustrate this point.

The engineering information manager from the Northern States Power Company in Minneapolis, Minnesota (84988) has maintained an active interest in fuel cells, combined cycle generating plants, and thermoelectric solar power since hearing them described at the conference. There is also a growing interest in these new generating methods within the company.

The head of the Planning Section of the Boston Edison Company in Massachusetts (84986) was particularly interested in the descriptions of boiler instabilities and direct energy conversion presented at the conference. Later, he ordered a NASA publication on boiler instabilities and plans to assign an engineer to study its application to the company's boilers.

A vice president of the Consolidated Edison Company of New York, Incorporated (84987) reported that the company subscribed to the services available from NASA's Regional Dissemination Centers, which were described at the conference. He also became aware of interesting advances in materials science through the conference presentations.

The manager of the Control and Instrumentation Division of Sargent and Lundy in Chicago, Illinois (84989) reported that he was seeking new technology at the conference for commercial application in the electric power industry. One instrument was described that interested him, but he later found that it was not available from any manufacturer, and the idea was dropped.

The manager of advanced technical planning at The Babcock and Wilcox Company's Research and Development Laboratory in Alliance, Ohio (84985) reported that his thoughts about future electric

**Preceding page blank**

power industry technology reflect an influence from the conference, particularly with respect to materials research on creep in high temperature applications.

**Control Numbers**

Tech Brief Number: None

NASA Center: Lewis Research Center

TRIS Case Numbers: 84985, 84986, 84987, 84988, 84989

TEF Number: 100

Date of Latest Information Used: November 28, 1972

## FRACTURE MECHANICS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Metal hardware and structures may contain flaws, or cracks, from the fabrication process or develop flaws during their service lifetime that can drastically affect the structural integrity of the part. For example, a relatively small crack in the surface of a large rocket propellant casing reduced the strength of the casing to half its conventional value and led to a catastrophic brittle-type failure during a pressure test. Similar examples of brittle fracture have occurred in other pressurized vessels, bridges and turbine-generators. The crack sensitivity of a metal component is dependent on both the component geometry and the plastic properties of the metal used. Methods that relate the actual strength of components containing flaws to measurable parameters of the component metal are rapidly developing in an engineering discipline called fracture mechanics.

Since the early 1960's, the Lewis Research Center has worked closely with the American Society for Testing and Materials (ASTM) on the development of standardized fracture mechanics test methods. Lewis researchers made major contributions to the test procedures, now recommended by ASTM, for measuring the important new material parameter of plane strain fracture toughness ( $K_{IC}$ ). The test methods are particularly significant in relating the characteristic plane strain stress condition for cracks in thick components to a measurable material property,  $K_{IC}$ . NASA has supported a large number of industrial contract programs that have developed fracture toughness data and analysis methods for materials, thicknesses, and configurations representing practical aeronautical and aerospace hardware. These programs also developed a methodology with which specific criteria for the selection of operational stress levels, proof test stress levels, inspection requirements, and inspection intervals can be established in a rational manner. Many contributions from Lewis and NASA-funded researchers have been described in ASTM Special Technical Publications. In addition, Lewis prepared a Technical Support Package (TSP), entitled *Survey of Fracture Toughness Test Methods*, that was announced by NASA in Tech Brief 68-10046.

In the mid-1950's there was a sudden increase in the number of brittle fracture failures of large steam turbine-generators. Increasing turbine sizes and conventional quality control inspection for turbine rotor forgings had produced a situation in which undetected small flaws were acted upon by larger operating stresses. The immediate problem was solved by the expensive method of more stringent quality control inspection. With the increased understanding of fracture mechanics, however, better material choices and the definition of acceptable flaws have significantly reduced the rejection rate of rotor forgings while maintaining quality standards on still larger turbines.

The General Electric Company in Schenectady, New York (85212) and the Westinghouse Electric Corporation in Pittsburgh, Pennsylvania (85204) have used the  $K_{IC}$  material test and other NASA-developed fracture mechanics technology in eliminating the catastrophic failure of turbine-generators. Researchers from both companies have participated with ASTM and Lewis in developing the discipline of fracture mechanics. General Electric has created design criteria for gas and steam turbines which incorporate both the  $K_{IC}$  value for materials and analytic methods derived under NASA funding.

The annual funding for fracture mechanics research at Westinghouse has grown from \$50,000 in the late 1950's to the present \$1,000,000. This effort, which involves fifteen professional researchers, is the largest industrial commitment to the discipline outside the aerospace industry. The NASA contributions

to the technology have been incorporated in applications related to turbines and nuclear reactor pressure vessels. Westinghouse has developed an alternative  $K_{IC}$  test specimen configuration, now accepted by the ASTM, and Lewis Research Center participated in the testing program which led to its acceptance. The company's in-house fracture toughness testing program has generated extensive data for turbine and pressure vessel steels.

NASA contributions to fracture mechanics are used in the new recommendations for nuclear reactors which appear in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code. These recommendations, published in the 1972 Summer Addenda, Section III, Appendix G, entitled "Protection Against Nonductile Failure," are based on the results of an investigation conducted by the Pressure Vessel Research Committee (PVRC) of the Welding Research Council (WRC). The WRC report, "PVRC Recommendations on Toughness Requirements for Ferritic Materials" (WRC Bulletin 175), incorporates methods for analyzing the stress-intensity factors ( $K_I$ ) of bolts and nozzles, which were developed at Lewis Research Center and under a NASA grant respectively. The report also presents a lower bound curve for  $K_{IC}$  values of pressure vessel steels. This curve is based on  $K_{IC}$  tests conducted by the Union Carbide Corporation (85214) during the Heavy Section Steel Technology (HSST) Program. This work was done under contract to the Atomic Energy Commission at the Oak Ridge National Laboratory in Tennessee. The HSST Program and other industry cooperative programs on pressure vessel steels have evolved from a 1966 report submitted to the AEC by PVRC. Lewis researchers have also served on the HSST Review Committee.

Two major producers of nuclear pressure vessels are Combustion Engineering, Incorporated, in Chattanooga, Tennessee (85208) and The Babcock and Wilcox Company in Alliance, Ohio (86001). Both companies plan to use the Appendix G recommendations for their product design and quality control inspection in the immediate future. The latter application is very important because, for the last six years, every flaw revealed by ultrasonic inspection has had to be removed. In addition to the expense and delay involved, repair work has caused greater problems than it solved in some cases. The new appendix provides a basis for judging what to do with the flaws discovered during fabrication and reactor operation. Both companies have conducted  $K_{IC}$  tests for their own research and development programs, and company spokesmen state that further development of fracture mechanics technology for nuclear reactor applications will be required.

Atomics International, a division of North American Rockwell Corporation in Canoga Park, California (85206), has been familiar with the  $K_{IC}$  test and other NASA contributions to fracture mechanics through the ASTM publications and the corporation's aerospace contract work. The company has used concepts from the NASA work to develop a test which measures the fatigue crack propagation rate for a material. A spokesman stated that, with the 1972 Boiler Code Addenda, reactor design applications of fracture mechanics will become important. Gulf General Atomic Corporation in San Diego, California (85203) is analyzing potential applications of the code recommendations in its reactor designs. Gulf is also interested in tests to predict fatigue crack propagation rates for reactor materials.

Researchers at the Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation in Richland, Washington (85201), have investigated the effect of cyclic frequency on the fatigue crack propagation in stainless steel using  $K_{IC}$  test specimens. The test results will be important in the design and analysis of components for the Liquid Metal Fast Breeder Reactor development program.

The Metallurgical Department of the Detroit Edison Company in Michigan (85211) is planning to conduct  $K_{IC}$  tests in 1973. Company scientists learned of the developments in fracture mechanics at the Lewis Research Center Conference on Aerospace Structural Materials held in 1969. In recent years, Detroit Edison has experienced problems in large rotating equipment, such as generators, with cracks leading to brittle fracture. The fracture toughness testing program is planned so that better inspection procedures can be devised to avoid the problem.

The Lapp Insulation Division of Interpace Corporation in LeRoy, New York (12475) has conducted fracture toughness tests of its high-voltage porcelain insulators based on the TSP. The company's test equipment did not provide data of sufficient reliability for the application, and the test program was terminated.

#### Control Numbers

Tech Brief Number: 68-10046

NASA Center: Lewis Research Center

TRIS Case Numbers: 12475, 85201, 85203, 85204, 85206, 85208, 85211, 85212, 85214, 86001

TEF Numbers: 124, 451

Date of Latest Information Used: January 23, 1973

## FUEL CELLS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Between 1958 and 1961 Pratt and Whitney Aircraft, a division of United Aircraft Corporation in South Windsor, Connecticut (84992), attempted to develop commercial fuel cells with in-house funds. By the end of 1960, the company was ready to drop the project since the developmental problems appeared to be too complex for economical solutions. At that point, Pratt and Whitney received a NASA contract to build a 250-watt demonstration fuel cell. Then in 1962, the company received a contract for 90 million dollars from the Manned Spacecraft Center to develop and manufacture the fuel cells for the Apollo spacecraft power plants. This contract extended the company's fuel cell work for five years and caused the construction of a production plant with over 300 trained employees.

The basic fuel cell chemical process, combining oxygen and hydrogen to form electricity and water, is over 100 years old. However, the materials and technology which made this process a practical reality have required extensive development. A fuel cell is made up of a stack of separated, individual fuel cell elements, each consisting of a fuel electrode, an electrolyte matrix and an air electrode. Some of the main attractions for the fuel cell are its relatively high efficiency (above 40 percent), almost total lack of any pollution emissions and its easy maintainability.

The fuel cells in Apollo consumed pure oxygen and hydrogen. Since these fuels are not available at an economical price for ground power applications, the specific materials used in the space cells are not suitable for ground units. Approximately 70 million dollars have been spent since 1962 in the development of commercial fuel cell technology so that standard gas and liquid fuels can be used with the oxygen from ambient air. Almost one-half of this amount was provided by a group of twenty-eight major gas and gas/electric utilities through a joint program that was formed in 1967 with Pratt and Whitney, called TARGET (Team to Advance Research for Gas Energy Transformation). The 12.5-kilowatt fuel cell modules produced for this program have operated almost 100,000 hours at 20 sites around the country. Based on the success of this unit, Pratt and Whitney has developed a much smaller unit with the same electrical rating which will be marketed in late 1973. Although the current model is cheaper to operate than the diesel generators with which it competes for a market, further development will be required to make the fuel cell economically feasible for widespread use.

Eleven electric utilities and the Edison Electric Institute are funding Pratt and Whitney's research on fuel cells in the 10- to 50-megawatt range for peaking power and distributed generating system applications. In 1972, this was a three million dollar effort. One potential application for units of this size would be in the utilization of hydrogen fuel, which may be produced during periods of low demand when the high temperature breeder reactor plants become operational in the 1980's.

### Control Numbers

Tech Brief Number: None  
 NASA Center: Manned Spacecraft Center  
 TRIS Case Number: 84992  
 TEF Number: 448  
 Date of Latest Information Used: January 1, 1973

**Preceding page blank**

## FUEL VAPORIZATION MODEL TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Since the mid-1950's, the Lewis Research Center has developed several analytic methods to investigate rocket engine combustion processes in order to improve combustion efficiency and rocket performance. One of the methods, a propellant vaporization model, was described in a 1960 NASA Technical Report (NASA TR R-67). This model has provided NASA in-house and contractor personnel with the basis for performing improved analyses of heterogeneous combustion processes.

The Lewis vaporization model was designed to provide local vaporization rates, mixture ratios, and combustion conditions for numerous combinations of propellants, engine design parameters and operating parameters. This permits the nonhomogeneous conditions in a combustor to be modeled locally. The heat and mass transfers that occur between introducing a fuel and final combustion are included in the model. A technique for using the calculated results in the design of rocket combustors is also described in the report. Experimental results at Lewis exhibit good agreement with the model predictions.

The Dynamic Science Division of Marshall Industries, under contract to Lewis, subsequently improved the model and prepared a corresponding computer program. This research eliminated the need for several assumptions that were used in the original model. NASA has also supported the development of computer programs that complement the vaporization model by analyzing the actual combustion kinetics and the chemical composition of exhaust gases (see Technology Transfer Example Summary "Computer Programs to Analyze Combustion").

In 1970 a group of aerospace combustion experts, including those who had conducted the vaporization model research at Dynamic Science, formed a new company, KVB Engineering, Incorporated in Tustin, California (87029). The new company has rapidly become a major combustion consulting firm for the electric utilities. The improved model is an integral part of the combustion analyses that KVB performs for electric power plant fossil-fired boilers. The analytic results are used to prescribe alterations in the hardware and operation of boilers. These alterations have reduced the formation of nitrogen oxides ( $\text{NO}_x$ ) between 40 and 70 percent. The reduction is achieved at minimal cost without degrading the safety, efficiency, or operating costs for the boilers. No presently available alternative approach to solving the  $\text{NO}_x$  emission problem for stationary power plants appears to be comparable in cost or effectiveness to the KVB methods. Approximately fifty boilers belonging to eight utilities have been adjusted in this manner to comply with emission standards set by law.

The vaporization model is crucial to the analysis of coal- and oil-fired boilers. KVB experts recently improved their analytic tools by coupling the vaporization program with a NASA contractor-developed chemical kinetics program to facilitate computer calculations. KVB has completed a successful preliminary test program on coal-fired boilers for the Arizona Public Service Company in Phoenix (87030). Minor adjustments were made in two boilers at the company's Four Corners Power Plant near Farmington, New Mexico for a three-week period, and a significant reduction in  $\text{NO}_x$  emissions was obtained. This was one of the first applications for the KVB techniques on coal-fired units. Arizona Public Service is currently considering a KVB proposal to conduct a more extensive study leading to permanent hardware and operation alterations in its coal-fired boilers.

Preceding page blank

**Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Numbers: 87029, 87030  
TEF Number: 464  
Date of Latest Information Used: February 9, 1973

## GAS TURBINE COOLING TECHNOLOGY TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The most important way to improve gas turbine efficiency is to increase the turbine inlet temperature. For units designed to operate above 1,800°F, the metallurgical limitations of commonly used alloys require the use of supplementary cooling techniques for components such as blades and vanes. The simplest technique, convection cooling, was first introduced around 1960 and is effective for inlet temperatures up to 2,200°F. At higher temperatures, the techniques of impingement cooling (up to 2,400°F), film cooling (up to 2,600°F), and transpiration cooling (above 2,600°F) must be used. However, the fabrication costs and structural problems associated with each technique increase substantially in the listed order. As a result, the highest operating temperatures in current commercial gas turbines are limited to about 2,400°F in the airbus-type aircraft where impingement cooling is used.

Prior to 1959, the Lewis Research Center conducted an extensive research and development program in turbine cooling technology. This work provided a technological base for the turbine cooling advances made by turbine manufacturers during the 1960's—particularly, convection cooling which is now commonly used. In addition to general cooling studies, the early results included studies of air and liquid cooled heat transfer mechanisms, fluid flow and heat exchangers. The effectiveness of different convection configurations was analyzed through design studies and hardware tests. The Lewis program was reactivated in 1966 and has since been directed toward the compilation of design information for turbine cooling and the evaluation of advanced cooling techniques, such as transpiration, for inlet temperatures up to 4,000°F and gas pressures up to 600 psia.

Pratt and Whitney Aircraft, a division of the United Aircraft Corporation in East Hartford, Connecticut (90556), has used information and data from the Lewis program in a continuing effort to improve the efficiency of its ground power turbine products. The company sold its first ground power unit in 1960, and the technology embodied in it was closely related to that in aircraft engines. In recent years, the growing distinction between aircraft and ground power units reflects an intensive R&D effort focused on the new application. The first units operated at about 28 percent thermal efficiency with a gas inlet temperature of 1,650°F; no cooling was required at this temperature. Today, 31 percent thermal efficiency is achieved with a gas inlet temperature of almost 2,000°F. Since the initial blade rows must be cooled at this temperature, Pratt and Whitney developed convection cooling methods for these units. The four examples cited below illustrate how company design engineers have used cooling technology from Lewis in this development.

An early Lewis report on one dimensional internal compressible flow (NACA TN 3150) provided the basis for calculating flow splits in turbine airfoil cooling cavities. Another early report on channel flow heat transfer (NACA TN 1451) has been used for the heat transfer coefficients in the inlet (sudden contraction) region of the turbine cascade. A 1969 report on discharge coefficients through small holes (NASA TN D-5467) provided supplementary data for estimating the size of holes required for cooling air flow. Two reports on coolant pressure and flow distribution (NASA TM X-2028 and NASA TM X-2472) contributed to the equations used in the design and analysis of convective, impingement and film cooling systems.

A Pratt and Whitney spokesman reported that it would be impossible to quantify the impact of these and other technical contributions from Lewis on the company's R&D program for high efficiency ground power gas turbine units. However, the Lewis contributions were used in achieving a ten percent

increase in ground power gas turbine thermal efficiency. Gas turbines currently generate about seven percent of the electricity in the United States.

**Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Number: 90556  
TEF Number: 469  
Date of Latest Information Used: July 10, 1973

## HEAT PIPE APPLICATIONS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The development of modern heat pipe technology was initiated in 1963 by George Grover of the Los Alamos Scientific Laboratories. The Atomic Energy Commission secured a patent only on the high-temperature heat pipe because it was discovered during a patent search that a similar device had been patented in 1942 for refrigeration uses. Grover's heat pipe was developed specifically to solve spacecraft thermal equilibrium problems. Sun facing surfaces of nonrotating satellites become excessively hot, while surfaces not exposed to the sun become very cold; the temperature differentials can cause failure of electronic and other spacecraft systems. One solution is to rotate the spacecraft, but in some satellite uses this is not possible or desirable. Grover's system transfers heat efficiently without recourse to pumps or other mechanical devices that might be subject to failure.

The heat pipe is a simple device, involving no moving parts. A mesh or wick is sealed inside a tube along with a working fluid. When the heat is applied to a portion of the pipe, the working fluid evaporates and fills the pipe, condensing on the walls at cooler segments of the pipe. This condensation releases heat. Pressure and temperature differentials within the pipe are small, and the heat transfer occurs almost isothermally. The isothermic characteristic makes possible a return flow of the condensed fluid by capillary action, completing the cycle. The heat pipe can operate over a wide temperature range depending on the nature of the working fluid, which can be water, molten metal, or any other appropriate fluid. Heat can be transferred with a heat pipe up to 500 times more efficiently than with any solid metal conductor.

Since the announcement of Grover's invention, NASA and several private companies have been investigating numerous fluids, geometry, wick materials, and operating characteristics of the heat pipe. NASA has also sponsored colloquia to describe the rapidly expanding heat pipe technology. The NASA-sponsored Regional Dissemination Center at the University of New Mexico, the Technology Application Center (TAC), provides heat pipe bibliographies and symposia.

Isothermics, Incorporated in Clifton, New Jersey (83601) was formed in 1971 to develop and market commercial products using heat pipe technology. The company subscribes to the TAC service for heat pipe technology, and its employees have attended symposia on the technology sponsored by TAC. Isothermics has marketed four product lines and plans to introduce two more in the near future. The products are used, for example, to increase the efficiency of home and industrial furnaces by recovering waste heat or to cool industrial brakes, electronics packages and motorcycle oil. The retail value of monthly shipments is over \$60,000 and is rapidly increasing. A company spokesman reported very good market response to new product announcements. Isothermics has applied for patents on heat pipe fabrication inventions related to sealing and internal fabrication methods which are basic to the mass production of reliable units. One of the two new products is a high voltage heat pipe for use in electric transformers and electronic packages. The size of a large transformer, for example, could be reduced by as much as 30 percent by using this heat pipe to dissipate heat.

The Donald W. Douglas Laboratories of the McDonnell-Douglas Corporation in Richland, Washington (86008) has developed and manufactured heat pipes for NASA and Air Force applications. Some of the applications developed for NASA include: heat transfer in spacecraft solar cell arrays to increase electric generating efficiency; prevention of moisture condensation in Skylab; and cloud physics experimental chambers for the space shuttle program. In addition to the heat pipe designs and

production capacity developed under contract, the company's researchers have created computer programs to aid in heat pipe design efforts. These capabilities have been used for the last three years to develop commercial heat pipe applications.

The company has produced almost 100 prototype units which are being evaluated in Alaska for solving structural problems caused by permafrost "jacking." This phenomenon, which also occurs to a lesser extent in other states, is caused by the annual freeze/thaw cycle in soils. Over a period of years, man-made structures are forced out of the soil by compressive forces from refreezing. The severity of the problem in Alaska is illustrated by the fact that electric power transmission poles must be replaced about every three years. The Golden Valley Electric Company is evaluating six of the McDonnell-Douglas heat pipes for transmission pole applications, and the preliminary results are very promising. Other Alaskan applications under evaluation include Alaskan oil pipelines supports and a Bureau of Indian Affairs school.

The heat pipes used in the Alaskan applications are twenty feet long, two inches in diameter and filled with ammonia. For installation, a hole is simply bored next to the structure and the heat pipe inserted. During cold winter months, the heat pipe drains more heat than usual out of the ground and creates a very solid freeze area under the structure. The heat pipe will not work in reverse, so the area remains frozen through the summer. "Jacking" is thus eliminated by preventing the thaw portion of the freeze/thaw cycle. The number of heat pipes needed for a given structure is determined by computing the size of the frozen area from temperature cycling data and knowledge of the heat pipe's cooling rate.

Commonwealth Edison Company in Chicago, Illinois (84982) supported a research program at the University of Illinois at Urbana-Champaign to study the use of heat pipes for cooling underground electric cables. One method for increasing the electrical carrying capacity of a cable is to cool it. The university researchers previously held NASA grants to conduct heat pipe experiments and to develop a system for detailed performance studies of heat pipes. These results were applied in the utility study to develop a "thermosyphon" heat pipe concept for dissipating excess heat from underground cables. Commonwealth Edison has initiated a five-year study program, based on the university's results, to develop practical applications for the concept in underground power transmission lines.

#### **Control Numbers**

Tech Brief Number: None  
NASA-AEC Center: Los Alamos Scientific Laboratories  
TRIS Case Numbers: 83601, 84982, 86008  
TEF Number: 197  
Date of Latest Information Used: February 1, 1973

## HIGH TEMPERATURE FATIGUE ANALYSIS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Knowledge of the inelastic behavior of metals under cyclic loading conditions is fundamentally important to the design of reliable operating hardware components. At elevated temperatures, inelastic deformation often occurs as a gradual change in shape when metal is subjected to stress—a process known as creep. Cyclic loading, which is due to recurring, rapid changes in the temperature or mechanical operating conditions, causes fatigue damage in a metal component. When these two mechanisms occur simultaneously in high temperature operating equipment, such as gas or steam turbines, design analysis becomes quite complex.

The Lewis Research Center has conducted analytic studies and testing programs in this area of materials behavior since the early 1950's. A primary objective in the research effort has been to develop methods for predicting gas turbine component service life based on material data obtained by laboratory tests. Although this complex problem has not been solved, several useful results have already come from the center's research activity.

Based on the assumption of a linear life-fraction damage rule, the prediction of creep-fatigue damage is obtained by adding the fractional damage due to each mode—creep and fatigue—separately. Lewis researchers have developed several methods for determining the fractional damage in each mode. One method provides upper and lower bounds analytically, and nearly all test data are in this predicted range. Another method uses techniques devised at Lewis for calculating the pure fatigue life “universal slopes” and the pure creep-rupture life. The universal slopes technique provides the basis for a third method, the “10 percent rule,” which is used to calculate a lower bound life from the fatigue process alone. More recently, a method called “strainrange partitioning” was developed at the center to simplify the laboratory testing and analyses that were necessary in applying the linear life-fraction damage rule. These different methods represent plateaus in the progress toward understanding the complex problem of creep-fatigue interaction and predicting component service life.

Through the years, Lewis researchers in this field have participated in the numerous professional activities of the American Society for Metals, the American Society for Testing and Materials, and the American Society of Mechanical Engineers (ASME). By serving on professional committees, providing test data and computer time to committee activities, and presenting technical papers both here and abroad, Lewis personnel have disseminated the results of the center's research in creep-fatigue interaction to design engineers throughout the world. In particular, the center has actively supported the ASME Subgroup on Elevated Temperature Design in the development of high temperature design codes (Code Case 1331). Since 1964, this code case has undergone seven revisions as advances were made in design analysis criteria for components operating about 800°F. In 1970 the linear life-fraction damage rule was included in the code case for the first time, although the rule was first described in 1952. Acceptance of the rule was due, in part, to the tests and analyses conducted at Lewis which demonstrated its usefulness as a predictive tool.

The Babcock and Wilcox Company in Alliance, Ohio (86000) uses prediction methods from Lewis in evaluating fabrication processes for steam boilers. The company has compared its own test results with predictions from the universal slopes technique, and a fairly accurate fit was obtained. Code Case 1331 is used at Babcock and Wilcox in the design of boilers and boiler tubing. Combustion Engineering, Incorporated, in Chattanooga, Tennessee (85207) is also using the high temperature code for steam

boiler designs. The predictive methods are particularly important for power plant installations which do not operate at a steady load, such as peaking and intermediate cycling units. Company researchers are considering the use of strainrange partitioning for this application.

Gulf General Atomic Corporation in San Diego, California (85202) is using the design methods from the code case in designing its new 1,000-megawatt high temperature gas reactors. To supplement the code case, the company has developed a specialized linear damage rule which is largely dependent on several Lewis results concerning creep analysis and test data for stainless steels. This rule has become a standard design technique at Gulf Atomic International, a division of North American Rockwell Corporation in Canoga Park, California (85205), has used the creep-fatigue analysis methods and stainless steel test data from Lewis in the company's proposed liquid metal fast breeder reactor design. The Aerojet Nuclear Company, a division of Aerojet-General Corporation in Idaho Falls, Idaho (85307), has used the strainrange partitioning method to analyze creep-fatigue test data for irradiated stainless steels, under contract to the Atomic Energy Commission. These tests were conducted in the materials research program for the development of liquid metal fast breeder reactor technology.

The two major manufacturers of turbine-generators are investigating applications for the predictive methods developed at Lewis in the design and analysis of steam turbine components. The General Electric Company in Schenectady, New York (85213) is actively interested in the methods for thermal fatigue analysis and strainrange partitioning for use in turbine designs. The Westinghouse Electric Corporation in Lester, Pennsylvania (86002) is comparing its existing test data with the universal slopes predictions in order to evaluate potential applications in product design and analyze the residual life in existing equipment.

#### **Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Numbers: 85202, 85205, 85207, 85213, 85307, 86000, 86002  
TEF Number: 450  
Date of Latest Information Used: January 30, 1972

## IMPROVED METHOD TO DETERMINE THICKNESS OF RADIATION SHIELDS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

An analytic study conducted by the University of Tennessee, under contract to the Marshall Space Flight Center, provided an improved method for determining the necessary thickness of nuclear radiation shields. The improvement is based on using a specified importance function and sampling scheme with the standard Monte Carlo method. The importance function incorporates the first term of the value function series. By using it instead of the conventional exponential transform technique, the variance of the dose buildup factor can be significantly reduced for the same computational time. The study results were announced by NASA in Tech Brief 68-10143.

Burns and Roe, Incorporated, a major design engineering company in Hempstead, New York (14155), needed a method for determining the shield thickness required to protect steam lines, turbines, and other components in nuclear power plants from radiation. After receiving the Technical Support Package, the company adopted the new method as its standard technique for shielding design. The technology was used in designing the operational Oyster Creek, New Jersey nuclear power plant, saving Burns and Roe three to four man-months of engineering time. Similar savings are anticipated on four other nuclear plants which are under construction or being designed by Burns and Roe.

### Control Numbers

Tech Brief Number: 68-10143  
NASA Center: Marshall Space Flight Center  
TRIS Case Number: 14155  
TEF Number: 252  
Date of Latest Information Used: December 4, 1972

## LIQUID IMPACT EROSION MODEL TECHNOLOGY TRANSFER EXAMPLE SUMMARY

In the development of liquid metal Rankine cycle turbines for electric power generation in space, NASA has supported research programs on the problem of turbine blade erosion by liquid droplet impact. This problem can become acute in the final turbine stages where the wet vapor content in the flow is high. Submicron-sized liquid droplets in the wet vapor are collected on the stationary blades. As larger drops are aggregated, they are swept to the edge of the blade and enter the vapor flow. These drops may cause erosion when they impact on the rotating blades.

Westinghouse Corporation, under contract to the NASA Pasadena Office, developed a general mathematical model of the liquid impact erosion process to provide a basis for predicting the erosion rate and improving blade configurations. The model is applicable to either liquid metal or water vapor. It is based on experimental observations and on the results of previous analytical studies of condensation in the vapor flow. Westinghouse also wrote a computer program for the model which provides calculations for the major elements of the erosion process: amount of moisture condensed in the turbine flow; amount of moisture deposited on the stationary blades; size of the droplets torn from the stationary blades; size and speed of the droplets striking the rotating blades, amount of blade material removed by the different impacts, and the aggregated material removed over time.

The computational results have been compared to the actual erosion in liquid metal and steam turbines. In both cases, the calculated results were within an order of magnitude of the actual erosion. This computer model was the first to provide a quantitative prediction of turbine erosion rates.

The computer model is used at the Westinghouse Large Turbine Division in Lester, Pennsylvania (84980) in designing large steam turbines as a qualitative guideline in the evaluation of new blading design and alloy erosion characteristics. As the analytic results become more refined, they will provide one of the criteria for judging proposed design trade-offs. Another Westinghouse application is in the analysis of moisture removal devices to improve their efficiency and, therefore, the efficiency of the steam turbine.

### Control Numbers

Tech Brief Number: 70-10613  
NASA Center: NASA Pasadena Office  
TRIS Case Number: 84980  
TEF Number: 443  
Date of Latest Information Used: October 18, 1972

**Preceding page blank**

**Preceding page blank**

**MANSON-HAFERD TIME-TEMPERATURE PARAMETER  
TECHNOLOGY TRANSFER EXAMPLE SUMMARY**

When a sustained load is applied to a metal specimen at elevated temperatures, the specimen may slowly elongate, or "creep," until it eventually ruptures. For each combination of temperature, load stress, and alloy, the interval of time until stress-rupture occurs must be measured or estimated so that designers can properly select alloys for the proposed operating life and conditions of new equipment. If a direct measurement of the stress-rupture time for a new alloy were required before it could be used in equipment with a 30-year operating life, the testing delay would preclude the use of the alloy. Therefore, extrapolation techniques for predicting long-term stress-rupture data on the basis of short-term test results have become increasingly important in new equipment design.

Stress-rupture data extrapolation is generally based on testing a specimen at the desired stress load with a temperature above the design condition so that stress-rupture will occur in a shorter time. The mathematical relations which make the transposition of temperature with time possible are called time-temperature parameters.

The Lewis Research Center has conducted tests and analyses related to time-temperature parameters since the early 1950's, when the center was part of the National Advisory Committee for Aeronautics (NACA). One of the first results, the Manson-Haferd parameter, was described in a 1953 NACA publication, entitled "A Linear Time-Temperature Relation for Extrapolation of Creep and Stress-Rupture Data" (NACA TN-2890). In the intervening years, this parameter has been evaluated for a large number of materials. For example, very close prediction, based on data from tests under 3,000 hours, of the measured results obtained in 100,000-hour tests of several steam turbine steels has been demonstrated. The Manson-Haferd parameter has frequently been cited and described in professional papers and textbooks.

Lewis' research in this technological field continues to generate new test data and more sophisticated approaches to the parametric analysis, such as incorporating the effects of metallurgical instability. The research staff has participated in the national and international professional activity (e.g., the American Society for Metals) related to the stress-rupture problem for a number of years.

Combustion Engineering, Incorporated, in Chattanooga, Tennessee (85209) uses the Manson-Haferd parameter as one of its standard methods for analyzing stress-rupture data for new alloys. The company's steam boilers for electric generating plants are designed according to the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, which specifies material and processing standards for the many boiler components. In order to receive a code stamped approval on a boiler, the company must have each new material used in the boiler approved by the relevant ASME code committee. The promising new alloys which Combustion Engineering regularly receives from suppliers must be tested for in-house evaluation and, should the company desire to use one, the code committee evaluation. Stress-rupture data from Combustion Engineering's tests are very important in the evaluation process, particularly for applications such as boiler tubing. The company saves considerable test time by using the Manson-Haferd parameter to extrapolate from these data for both evaluations. In addition, the parameter accelerates the rate at which the company can improve its boilers with new alloys.

The Detroit Edison Company in Michigan (85210) will use the Manson-Haferd parameter to extrapolate from its stress-rupture tests on superheater tubing for steam plant boilers. The current tests

are the first extensive tests of this sort that the company has conducted. The results will be used to provide information for monitoring existing units and to evaluate design proposals for new units. Boiler tubing is a major cause of forced outage in power plants, since a total shutdown is caused by the breakage of a single tube among the hundreds which are found in a steam boiler.

**Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Numbers: 85209, 85210  
TEF Number: 449  
Date of Latest Information Used: January 13, 1973

## NASTRAN TECHNOLOGY TRANSFER EXAMPLE SUMMARY

The NASA Structural Analysis Program (NASTRAN) is a general purpose, digital computer program designed to analyze static and dynamic behavior of elastic structures and to display a summary of the computed structural behavior with standard computer plotters. The program was, and still is, used by NASA and aerospace companies to design and analyze aircraft fuselages, wings and tail assemblies, space vehicles (Viking and Skylab) and their related launch facilities, and turbine engines.

The wide range of analytic capability built into NASTRAN includes: static structural response to concentrated and distributed loads; thermal expansion and enforced deformation; dynamic structural response to transient loads; steady-state harmonic loads and random excitation; and determination of real and complex eigenvalues for use in vibration analysis, dynamic stability analysis and elastic stability analysis. The program is highly user-oriented through an easy data input format, error message vocabulary, and annotated, modular output format. The output plotting may be selected from a variety of structural and curve plotting options. NASTRAN can handle structural problems of virtually unlimited size.

Between 1965 and 1970, Goddard Space Flight Center developed the program through a combination of in-house and contracted research for approximately \$3,000,000. Five Special Publications which describe different aspects of NASTRAN resulted: SP-260, SP-221, SP-222, SP-223 and SP-224. The first document, SP-260, is a general summary of NASTRAN functions and capabilities; the other four describe the theory, use, programming, and sample problems related to it. After Goddard programmers and engineers completed NASTRAN's development, it was released to public users in November 1970. The program, as is the case with most NASA computer programs, is being disseminated at cost by the Computer Software Management and Information Center (COSMIC) at the University of Georgia, under contract to NASA. In 1971 NASA published Tech Brief 71-10285 to announce the program's availability from COSMIC and the NASA publications which describe it. A set of NASTRAN tapes and documentation can be purchased from COSMIC for an average cost of \$1,700, depending on the options required by the user.

The Handford Engineering Development Laboratory (HEDL) in Richland, Washington (84977) is using NASTRAN in its development of the Fast Flux Test Facility (FFTF) for the AEC Liquid Metal Fast Breeder Reactor Program. In FY 1972 alone, NASTRAN was used for more than 200 computer hours in dynamic modeling of the FFTF design under simulated earthquake and accident conditions. Although the program is usually run on the HEDL computer, it was recently made available on the huge Control Data Corporation 7600 computer at the Lawrence Radiation Laboratory in Berkeley, California; the larger FFTF dynamic models have used this machine. NASTRAN is currently being used to develop a generalized vibration model for scaling up the one-fourth size FFTF mock-up which is complete with vessel, core, instruments and piping. Vibration tests of the mock-up (either by using an external shaker or by running water through the piping) provide input data for NASTRAN in deriving the lumped-mass model.

Gulf General Atomic Corporation in San Diego, California (84981) has used NASTRAN for almost a year in dynamic modeling of the company's high temperature gas-cooled reactors (HTGR). The primary application is in vibration analysis for the verification of hardware designs under earthquake and flow-induced oscillation conditions. Although most of the modeling was for the 1,000-megawatt HTGR

currently being developed, the program was used to model the 300-megawatt Fort St. Vrain Nuclear Generating Station which is under construction in Colorado. Gulf has also used the program to analyze HTGR support structures for buckling characteristics. NASTRAN is now used only if no other program will do the job; but as Gulf engineers become more familiar with it, this use is expected to increase.

Westinghouse Electric Corporation in Pittsburgh, Pennsylvania (86003) has used NASTRAN since 1970. Company engineers became interested in the program while it was still being developed at Goddard. Some of the company's divisions use the program through the research center computing facility in Pittsburgh, while others, such as the Steam Turbine Division in Lester, Pennsylvania, have the program in their own computers. The accumulated running time for NASTRAN on the company's large computers is estimated to be as much as 300 hours. Applications include: elastic analysis of natural frequencies for steam turbine blades; transient response and thermal analysis of turbomachinery housings; and analysis of structures such as floating nuclear power plants. Westinghouse has received orders for two of the floating power plants to be constructed in the late 1970's. In most of these applications, NASTRAN performs calculations which were not economically feasible with previous computer program capabilities. A company spokesman reported that the NASA program is becoming an important design tool for Westinghouse engineers.

#### **Control Numbers**

Tech Brief Number: 71-10285  
NASA Center: Goddard Space Flight Center  
TRIS Case Numbers: 84977, 84981, 86003  
TEF Number: 410  
Date of Latest Information Used: January 30, 1973

## NUCLEAR AND ATOMIC PHYSICS HANDBOOK TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Many personnel involved in field testing of nuclear rockets have been found to have inadequate or no background in the fundamentals of nuclear or atomic physics; also, many do not have the preparation in calculus and other areas of advanced mathematics that is necessary to study most existing texts on the subject. To remedy this situation, the Space Nuclear Systems Office (formerly the Space Nuclear Propulsion Office) contracted with Westinghouse Astronuclear Laboratory and Aerojet-General Corporation to produce a handbook that explains nuclear and atomic physics in a simple manner. The handbook, written by D. F. Hanlen and W. J. Morse, gives an overview of nuclear, atomic, and reactor physics, including discussions of atomic structure ionization, isotopes, radioactivity and reactor dynamics. Calculus is not used; all equations are carefully explained; and the text can be understood by high school students with some science background. The handbook is available from NASA as TSP 69-10705.

Several firms use the handbook in training programs as well as general information for nonspecialist employees. The Florida Power Corporation in St. Petersburg (46785) has been using the handbook as an introductory text in training programs for nuclear power plant operators. A 20-week program commencing in January 1973 will use the handbook as a supplement to a text written specifically for the program. Burns and Roe, Incorporated, a major design engineering firm in Hempstead, New York (34992), requires its design engineers to familiarize themselves with nuclear power plant processes by using the handbook. This orientation method has saved considerable study time in expanding their engineering background to include an understanding of nuclear processes for design problems such as radiation shielding.

An engineer with the Los Angeles Water and Power Company (45706) used the handbook to acquire most of this basic understanding of the physical phenomena which occur in a nuclear reactor for power generation. The company was in the initial stages of nuclear power plant installation, and the engineer applied the information to his work on fuel cost analysis. The computerized analysis has provided 50-year projections for company planners.

Nonspecialists in the Electro-Mechanical Division of Westinghouse Electric Corporation in Cheswick, Pennsylvania (45928) have used the handbook for background information related to the division's pump products for nuclear reactor installations. Many personnel without an extensive background in nuclear physics require at least a general familiarity with the subject. Administrators, purchasers, health and safety personnel, and others have read the handbook for this background.

Engineers at Pacific Pumps in Huntington Park, California (45742) used the handbook for background information about materials for nuclear installations. The information helped the firm in acquiring certification as a supplier of pumps for nuclear facilities.

### Control Numbers

Tech Brief Number: 69-10705  
 NASA-AEC Center: Space Nuclear Systems Office  
 TRIS Case Numbers: 34992, 45706, 45742, 45928, 46785  
 TEF Number: 403  
 Date of Latest Information Used: December 4, 1972

## POTASSIUM RANKINE CYCLE TEST PROGRAM TECHNOLOGY TRANSFER EXAMPLE SUMMARY

During the 1960's, NASA and the Atomic Energy Commission conducted extensive research for the Systems for Nuclear Auxiliary Power (SNAP) program. The Lewis Research Center had a major program responsibility to develop liquid metal and materials technology for SNAP applications such as the nuclear core coolant and the turboalternator working fluid (Rankine cycle). The liquid metal testing programs conducted by Lewis and its contractors have produced tens of thousands of operating hours in these applications. A major advantage of the liquid metal systems is in their higher operating temperatures (to 1,500°F) at low pressure, which allow a higher power density for the system.

The General Electric Company in Cincinnati, Ohio (86004) established several potassium test facilities, under contract to the Lewis Research Center, starting with the Potassium Turbine Test Facility in 1961. The company subsequently received almost \$30 million in Lewis contracts for research and development of potassium technology. Primarily, this effort was to design, test, and evaluate the performance and endurance of two stages of a five-stage, one-half-megawatt turbine driven by potassium vapor. Two of the major results from the tests were fluid dynamic design method verification for potassium turbines and the characterization of wet potassium vapor erosion properties for turbine component alloys. In addition, basic heat transfer data for the boiler, condenser, and other system components were obtained during the tests.

General Electric is conducting a design study and economic analysis for a 1,300-megawatt binary cycle power generating plant under contract to the Office of Coal Research and the Lewis Research Center. The binary cycle would consist of a high temperature (1,500°F) topping cycle turbine generator with potassium as the working fluid and a normal temperature (1,050°F) cycle with a steam turbine generator. Heat from the condensing potassium vapor would raise steam for a conventional steam turbogenerator. A significant increase in power generating efficiency is possible with the binary cycle, with estimates ranging from 45 to 55 percent. Standard fossil-fueled steam plants are achieving up to 40 percent efficiency, and this figure is not expected to increase.

Prior to General Electric's current research on binary cycles, the company had discontinued its development of these systems. Between 1917 and 1949, General Electric built several binary cycle power plants using mercury vapor and steam. A company spokesman reported that the last of these plants was operating at almost 50 percent efficiency when it was shut down in 1968. Further development of the mercury/steam binary cycle plants was discontinued due to the costs of mercury and fabrication and the corrosion problems in the mercury cycle. These factors limited the binary cycle plant size to 40 megawatts and its highest temperature to 950°F. Since very little data were available for other liquid metals in the early 1960's, it was not economically feasible for General Electric to develop alternative binary cycle systems. However, when these data became available from the NASA-sponsored test facilities, the company resumed its interest in developing binary cycles, with potassium replacing mercury.

The advantages of potassium over mercury for this application include lower cost, vapor pressure and corrosion characteristics. For example, only minimal amounts of expensive, high temperature superalloys would be required for boiler tubing and other components, since the vapor pressure of potassium at 1,400°F is only one atmosphere. The NASA-funded testing program at General Electric was instrumental in demonstrating the low corrosion characteristics of potassium for power generation applications.

Preceding page blank

**Control Numbers**

Tech Brief Number: None  
NASA Center: Lewis Research Center  
TRIS Case Number: 86004  
TEF Number: 454  
Date of Latest Information Used: March 30, 1973

## RELIABILITY AND QUALITY ASSURANCE FOR NASA PROGRAMS TECHNOLOGY TRANSFER EXAMPLE SUMMARY

Since 1960, NASA has made great progress in applying quality assurance to support the development and management of unique space hardware systems. Broadly applicable concepts were created and implemented in quality management planning, quality assurance technology such as nondestructive testing, and failure prevention through analysis of fabrication details. The first NASA-wide quality assurance requirements document for contractors was *Quality Program Provisions for Space System Contractors* (NPC 200-2), issued in 1962. This document established a general quality program policy which could be applied to any major development project. It required the documented implementation of contractor-written quality program plans for each major project. The contractor plan presented the specifics of compliance to NPC 200-2, subject to NASA approval, such as inspection procedures and applications, scheduling on a systems matrix, and management of the contractor quality program. The documentation included a broad range of reports, management reviews, nondestructive test results and other relevant documents. For major programs, such as Apollo, NASA also issued a separate Project Development Plan that provided direction in applying policies, procedures, and requirements with an auditing procedure for evaluating NASA and contractor progress.

While NPC 200-2 was in draft form during 1961, it was extensively reviewed by quality assurance management personnel from NASA and the Department of Defense. Subsequently, the Department of Defense issued a similar, generic quality assurance program requirement, MILQ 9858A, for its contractors to replace some of the Department's previous, hardware-oriented requirements such as MILQ 9858. In 1970 the Atomic Energy Commission also issued the same type of requirement, based directly on MILQ 9858A, for the construction of nuclear power plants by electric utilities. During the 1960's, when nuclear plants were small and very conservatively designed, the AEC quality requirement (10-CFR-50) resembled the earlier military document (MILQ 9858), and little documentation was required. With the advent of large (1,000 Mw), complex nuclear plant designs in the late 1960's, a much more comprehensive quality assurance requirement became necessary, and Appendix B to 10-CFR-50 was published in July 1970. In addition to establishing a quality program policy for nuclear plant design and construction, the Appendix also requires extensive documentation and evaluation audits. The documentation for a single plant, from initial design stages to operational status, amounts to something like two and one-half million pieces of paper. These stipulations must be met before the AEC can issue a license to operate the plant.

In 1962, the General Electric Company's Space Division received a NASA contract to provide equipment and engineering services for the Apollo program at Cape Canaveral (later changed to Cape Kennedy). This part of GE was named Apollo and Ground Systems (AGS) and was headquartered in Daytona Beach, Florida (84976). AGS provided documentation management, program management support, system safety testing, identification and analysis of quality and reliability problems, and other services. Almost half of the 650 million contract dollars AGS received on the Apollo program was related to the implementation of the NASA quality assurance policies. AGS introduced its Nuclear Quality Assurance Consulting Service in 1969 for marketing these capabilities to utilities and contractors in the nuclear power industry. The service has been expanded to provide computer data and information management, training programs, organization of utility quality assurance programs, manuals and procedures for utilities and their contractors, auditing and technical consulting. To date, four utilities, including Commonwealth Edison and the Florida Power Corporation, have contracted with AGS for its services related to twelve nuclear power plants. In addition, there are five nuclear plant contractors using

the services. Two particular services which have become important since Appendix B was issued are auditing and documentation management. The Tennessee Valley Authority in Knoxville, Tennessee (84978), for example, is using the AGS auditing service to comply with Appendix B requirements for two nuclear plants with a total designed generating capacity of 4,800 megawatts now under construction. TVA selected AGS on the basis of its previous quality assurance experience in the space program and with other utilities on nuclear plants. An AGS proposal to provide computer-based information management services, such as documentation, for the two new plants is also under consideration at TVA.

Another way that General Electric has used the AGS experience is through the transfer of AGS personnel to commercial product groups. Two examples illustrating this point involve individuals from the AGS facility at the Manned Spacecraft Center in Houston. In 1966 a reliability management consultant for the Apollo program transferred to GE's Power Delivery Group in Philadelphia, Pennsylvania (87033), which produces electric power transmission and distribution equipment. In his new capacity as a consulting engineer, he used Apollo program reliability prediction methods in developing reliability and availability predictions for high voltage direct current (200,000 volts) valves and terminals. He is also participating in the Conference Internationale des Grands Reseaux Electriques (CIGRE) working group for reliability of power circuit breakers. Through his participation in this group, the Apollo program qualification tests for small circuit breakers are now serving as a benchmark in the definition of environmental and mechanical endurance tests for power circuit breakers for other member countries in CIGRE.

The second example involves an individual who transferred to the Large Steam Turbine-Generator Department in Schenectady, New York (87031) in 1971. He had been active in drafting contractor reliability requirements for the Space Shuttle program within the context of NASA's general quality program specifications. As a reliability engineer in the turbine-generator group, he initiated a comprehensive failure data system, a failure analysis facility, and failure mode analyses that were similar to those at AGS for the company's automatic turbine controller products. The failure rate for GE's electro-hydraulic controller, which was first introduced in 1968, has been significantly reduced as a direct result. The engineer has worked closely with control designers; and, as a result, the second generation of electro-hydraulic controllers incorporates redundancy, voting logic, and component selection concepts which he learned at AGS.

Valcor Engineering Corporation in Kenilworth, New Jersey (84979) has applied quality assurance management skills and technical capability, acquired for the space program, to its manufacture of valves used in liquid metal fast breeder reactor research. This market is a sizeable segment of the company's five million dollar annual business. Valcor supplied valves for liquid metal applications in the Systems for Nuclear Auxiliary Power (SNAP-8) development conducted by Aerojet-General Corporation under contract to Lewis Research Center. Although the specific requirements of the two programs are different, a company spokesman stated that documentation and management capabilities in materials traceability and control developed for SNAP are directly applicable to the quality assurance requirements in the new market. Prior to its space program work, the company conducted its quality control by pressure testing the valves; it had to develop an in-house nondestructive testing capability for SNAP. These technical skills were easily adapted to the new requirements.

Ontario Hydro in Toronto, Canada (87032) is using the general NASA contractor reliability requirements as a guide in developing new contractor specifications that will include requirements such

as failure data management systems and the use of reliability data in design. The company is one of the largest producers of electric power in North America, with over 2,400,000 customers and almost 15,000 megawatts of generating capacity in hydroelectric, fossil steam, nuclear and gas turbine plants. The supervising reliability engineer in the Generation Concepts Department became familiar with the NASA reliability publications through the professional journals and meetings of the Institute of Electrical and Electronics Engineers (IEEE). He has presented professional papers describing the application of reliability and maintainability to generating plants. These applications include design review and reliability program evaluation concepts from NASA publications.

**Control Numbers**

Tech Brief Number: None

NASA Center: Kennedy Space Center, Lewis Research Center, Manned Spacecraft Center

TRIS Case Numbers: 84976, 84978, 84979, 87031, 87032, 87033

TEF Number: 444

Date of Latest Information Used: February 9, 1973

**ROCKET ENGINE STEAM GENERATOR  
TECHNOLOGY TRANSFER EXAMPLE SUMMARY**

The Rocketdyne Division of North American Rockwell Corporation in Canoga Park, California (84991) has become the nation's leading producer of high thrust liquid propellant rocket engines. All NASA manned space flights have used Rocketdyne engines; and the Saturn V engines, in particular, were developed under contract to the Marshall Space Flight Center. This NASA-funded rocket engine development led to an increase in heat flux capability of almost two orders of magnitude through the use of better materials, construction techniques and cooling methods. Substantial improvements were also made in the technology for using liquid fuels, such as hydrogen, and for better combustion efficiency.

In June 1972, Rocketdyne and Commonwealth Edison Company in Chicago, Illinois (84990) announced a jointly funded project to install an adapted rocket engine for generating the steam used in an existing Edison plant near Joliet, Illinois. The installation, which is expected to cost about 1.6 million dollars, will produce 11 megawatts for peaking power starting in late 1973.

The Rocketdyne power unit will be fueled by liquified natural gas and oxygen to produce steam for a conventional turbine-generator. It will replace a coal-fired boiler which is approximately 500 times larger. In addition to being much more compact, the new combustor will have virtually no particulate or other pollutant emissions. The two companies announced that it would mark the first earth adaptation of power units developed for Saturn V and other NASA launch vehicles. The joint venture culminated a year-long study of the proposed application.

**Control Numbers**

Tech Brief Number: None  
NASA Center: Marshall Space Flight Center  
TRIS Case Numbers: 84990, 84991  
TEF Number: 447  
Date of Latest Information Used: October 25, 1972

**Preceding page blank**

## REFERENCES

- Arrow, Kenneth. "Economic Welfare and the Allocation of Resources for Invention," in *The Rate and Direction of Inventive Activity*. A report of the National Bureau of Economic Research, Special Conference Series No. 13. Princeton, New Jersey: Princeton University Press, 1962.
- Barrett, S. "R&D: The Ball is Rolling—Do You Have a Program?" *Electric Light and Power (T/D Edition)*, January 1972, pp. 40-47.
- Belinfante, A. E. E. "Technical Change in the Steam Electric Power Generating Industry." Unpublished Doctor's dissertation, University of California at Berkeley, 1969.
- Benedict, M. "Electric Power From Nuclear Fission," *Science and Public Affairs: Bulletin of the Atomic Scientists*, XXVII (September 1971), 8-16.
- Berling, J. T., and T. Slot. "Effect of Temperature and Strain Rate on Low-Cycle Fatigue Resistance of AISI 304, 316 and 348 Stainless Steels," in *Fatigue at High Temperature*. ASTM Special Technical Publication No. 459. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1969.
- Bowen, Richard G. "Environmental Impact of Geothermal Development," *AWARE Magazine*, May 1973.
- \_\_\_\_\_, and E. A. Groh. "Geothermal—Earth's Primordial Energy," *Technology Review*, LXXIV (October/November 1971), 42-48.
- Breen, Bernard P. Vice President, KVB Engineering, Incorporated, Tustin, California. Telephone interview on November 28, 1972.
- Brown, F. Stewart. "Power Failures Caused by Severe System Disturbance," in *Proceedings of the American Power Conference*. Vol. 28. Chicago: Illinois Institute of Technology, Technology Center, 1966.
- "Codes, Standards, and the ASME; Part 2 - ASME Boiler and Pressure Vessel Codes," *Mechanical Engineering*, XCIV (July 1972), 16-18.
- Cook, E. "The Flow of Energy in an Industrial Society," *Scientific American*, CCXXIV (September 1971), 134-144.
- Diercks, D. R., and Masaki Kitagawa. "Comparison of High-Temperature Fatigue Data with Results of Selected Predictive Methods." Paper submitted for presentation at the International Conference on Creep and Fatigue in Elevated Temperature Applications, Philadelphia, Pennsylvania, September 23-28, 1973. Argonne, Illinois: Argonne National Laboratory, December 1972. (Mimeograph)
- Downs, Jack E. "Forced Outages of Large Steam Turbines - An Analysis of Causes," in *Proceedings of the American Power Conference*. Vol. 32. Chicago: Illinois Institute of Technology, Technology Center, 1970.

- Ecabert, R. J. "Steam Generators for Combined Steam and Gas Turbine Plants," *Journal of Engineering for Power*, October 1966, pp. 402-409.
- Electric Research Council, R&D Goals Task Force. *Electric Utilities Industry Research and Development Goals Through the Year 2000*. ERC Publication No. 1-71, June 1971.
- Energy Study Group. *Energy R&D and National Progress*. Report prepared for the Interdepartmental Energy Study by the Energy Study Group, under the direction of Ali Bulent Cambel. Washington, D. C.: Government Printing Office, [1964].
- Federal Power Commission. *The 1970 National Power Survey; Part I*. Washington, D. C.: Government Printing Office, December 1971.
- Foster-Pegg, R. W. "Trends in Combined Steam-Gas Turbine Power Plants in the U. S. A.," *Transactions of the ASME: Journal of Engineering for Power*, October 1966, pp. 302-309.
- Fraas, A. P. "A Potassium-Steam Binary Vapor Cycle for a Molten-Salt Reactor Power Plant," *Journal of Engineering for Power*, October 1966, pp. 355-366.
- "Gas Turbines, Steam Units Combine for Economy," *Electrical World*, February 23, 1970, pp. 28-29.
- Gordon, Dr. Robert. Director of Quality Standards and Reliability, Consolidated Edison Company of New York, Incorporated, New York. Telephone interview on February 27, 1973.
- Gordon, Sanford, and Bonnie J. McBride. Physical Chemistry Section, Physical Science Division, Office of Space Technology and Materials, NASA Lewis Research Center, Cleveland, Ohio. Personal interview on December 4, 1972.
- Greenberg, H. D., *et al.* "Application of Fracture Mechanics Technology to Turbine-Generator Rotors." Paper presented at the 1969 annual meeting of the American Society of Mechanical Engineers, November 17, 1969.
- Gregory, Derek P. "The Hydrogen Economy," *Scientific American*, CCXXVIII (January 1973), 13-28.
- Halford, Gary R. "Fatigue in the Creep Range - Material Testing, Documentation and Interpretation." Position paper prepared for the [ASME] Creep-Fatigue Task Force. Cleveland, Ohio: NASA Lewis Research Center, January 1973. (Mimeograph)
- \_\_\_\_\_, M. H. Hirschberg, and S. S. Manson. *Temperature Effects on the Strainrange Partitioning Approach for Creep-Fatigue Analysis*. NASA TM X-68023. Cleveland, Ohio: NASA Lewis Research Center, 1972.
- Harmon, Robert A. "Gas Turbines: An Industry with Worldwide Impact," *Mechanical Engineering*, March 1973, pp. 33-59.
- Hauser, Thomas R., and Carl M. Shy. "Position Paper: NO<sub>x</sub> Measurement," *Environmental Science & Technology*, VI (October 1972), 890-894.

- Hayes, William C. Editor-in-Chief, *Electrical World*, New York, New York. Personal correspondence to the authors on May 7, 1973.
- Hopkins, Dr. Albert. "Guidance Computer Design," in *Space Navigation Guidance and Control*, ed. J. E. Miller. The Advisory Group for Aerospace Research and Development of the North Atlantic Treaty Organization: AGARDOGRAPH 105. Maidenhead, England: Technivision Limited, 1966.
- Hubbert, M. King. "The Energy Resources of the Earth," *Scientific American*, CCXXIV (September 1971), 60-84.
- Humphries, James J., Jr., and Donald H. Guild. "Technical and Economic Features of Stone & Webster's Fast Combined-Cycle Power Plants," in *Proceedings of the American Power Conference*. Vol. 33. Chicago: Illinois Institute of Technology, Technology Center, 1971.
- Jakub, M. Staff Engineer, Gulf General Atomic Corporation, San Diego, California. Telephone interview on January 12, 1973.
- James, David. Product Design Supervisor, Air Pollution Control Section, Power Generation Division, The Babcock and Wilcox Company, Barberton, Ohio. Telephone interview on January 16, 1973.
- Jarvis, Gene. Manager of Product Development, TRW Controls, TRW, Incorporated, Houston, Texas. Telephone interview on November 29, 1972.
- Jones, Reginald H. "The Energy Crisis in Perspective." Address to the Commonwealth and Commercial Clubs, Cincinnati, Ohio, January 17, 1973.
- Kalman, R. E., and T. S. Englar. *A User's Manual for the Automatic Synthesis Program (Program C)*. NASA CR-475. Washington, D. C.: National Aeronautics and Space Administration, June 1966.
- Kaufman, J. G. Chief, Mechanical Testing Division, Alcoa Research Laboratories, Aluminum Company of America, New Kensington, Pennsylvania. Telephone interview on October 5, 1971.
- \_\_\_\_\_. "Progress in Fracture Testing of Metallic Materials," in *Review of Developments in Plane Strain Fracture Toughness Testing*. ASTM-NASA Special Technical Publication No. 463. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1970.
- Khol, Ronald. "Can Technology Survive Bureaucracy? Part Two: Uncle Sam at the Helm," *Machine Design*, April 5, 1973, pp. 98-104.
- Kliegel, Dr. James R. President, KVB Engineering, Incorporated, Tustin, California. Telephone interview on November 28, 1972.
- Kosvic, T. Staff Scientist, KVB Engineering, Incorporated, Tustin, California. Telephone interview on February 9, 1973.
- Lamont, John W., and J. R. Tudor. "Survey of Operating Computer Applications," in *Proceedings of the American Power Conference*. Vol. 32. Chicago: Illinois Institute of Technology, Technology Center, 1970.

- Landsberg, H. H., and S. H. Schurr. *Energy in the United States: Sources, Uses, and Policy Issues*. New York: Random House, 1968.
- Long, W. W. Associate Director, Technology Application Center, University of New Mexico, Albuquerque. Telephone interview on January 16, 1973.
- McDonald, Dr. John P. Research Scientist, Philadelphia Electric Company, Pennsylvania. Telephone interview on January 2, 1973.
- \_\_\_\_\_, and H. G. Kwatny. "Design and Analysis of Boiler-Turbine-Generator Controls Using Optimal Linear Regulator Theory." Paper to be published in *Proceedings of the 13th Joint Automatic Control Conference*, [1972].
- McElhcnny, V. "Energy Shortage and Energy Choice," *Technology Review*, January 1971.
- Manson, S. S. Chief, Materials and Structures Division, NASA Lewis Research Center, Cleveland, Ohio. Personal interview on October 26, 1972.
- \_\_\_\_\_. *The Challenge to Unify Treatment of High-Temperature Fatigue - A Partisan Proposal Based on Strainrange Partitioning*. NASA TM X-68171. Cleveland, Ohio: NASA Lewis Research Center, 1972.
- \_\_\_\_\_. "Time-Temperature Parameters - A re-evaluation and Some New Approaches." Paper prepared for the American Society of Metals, June 10, 1969. Cleveland, Ohio: NASA Lewis Research Center, 1969.
- \_\_\_\_\_, G. R. Halford, and D. A. Spera. "The Role of Creep in High Temperature Low Cycle Fatigue," in *Advances in Creep Design*, eds. A. I. Smith and A. M. Nicolson. New York: John Wiley & Sons, Inc., 1971.
- Meinel, A. B., and M. P. Meinel. "Is It Time for a New Look at Solar Energy?" *Science and Public Affairs: Bulletin of the Atomic Scientists*, XXVII (October 1971), 32-37.
- National Aeronautics and Space Administration. *Selected Technology for the Electric Power Industry*. Proceedings of a technology utilization conference held at Lewis Research Center, Cleveland, Ohio, September 11-12, 1968. NASA SP-5057. Washington, D. C.: 1968.
- Nelson, Richard. "The Simple Economics of Basic Scientific Research," *Journal of Political Economy*, June 1959.
- Oldenburger, Rufus. "Automatic Control: A State-of-the-Art Report," *Mechanical Engineering*, April 1965, pp. 39-45.
- Olmsted, Leonard M. "23rd Annual Electrical Industry Forecast," *Electrical World*, September 15, 1972, pp. 55-70.

C-2

Paris, Paul C., and George C. Sih. "Stress Analysis of Cracks," in *Fracture Toughness Testing and its Applications*. ASTM-NASA Special Technical Publication No. 381. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1965.

"Planners Tell Preference for Gas Turbines and Diesels," *Electrical World*, July 7, 1969, p. 43.

Priem, Richard J. Head, Propellant Safety Section, Rocket Technology Branch, Launch Vehicles Division, NASA Lewis Research Center, Cleveland, Ohio. Personal interview on December 5, 1972.

Robson, F. L., and A. J. Giramonti. "A Note on Gas Turbine Development," *Technology Review*, LXXIV (December 1971), 60.

Rosenthal, Kermit. Associate Engineer, Southern California Edison Company, Rosemead, California. Telephone interview on November 28, 1972.

Ryan, Frank M. "Computers in the Plant," *Control Engineering*, September 1966, pp. 84-86.

Satterfield, Charles N. "Nitrogen Oxides: A Subtle Control Task," *Technology Review*, LXXV (October/November 1972), 10-18.

Schloesser, V. V. "A Large Peaking Gas Turbine," in *Proceedings of the American Power Conference*. Vol. 32. Chicago: Illinois Institute of Technology, Technology Center, 1969.

Seabrook, Henry H., and Bernard P. Breen. "A Practical Approach to NO<sub>x</sub> Reduction in Utility Boilers." Paper presented at the American Power Conference, Chicago, Illinois, April 18-20, 1972. Tustin, California: KVB Engineering, Inc., 1972.

Smith, Dr. Richard. Supervisor, Metal Property Technology, Research and Development Laboratories, Combustion Engineering, Incorporated, Chattanooga, Tennessee. Telephone interview on January 13, 1973.

Sonderling, Hans H. Staff Mechanical Engineer, Los Angeles Department of Water and Power, California. Telephone interview on February 7, 1973.

\_\_\_\_\_, *et al.* "How L. A.'s Tough NO<sub>x</sub> Limit Is Met At Scattergood," *Electric Light & Power (E/G Edition)*, January 1972.

Starr, Chauncey. "Energy and Power," *Scientific American*, CCXXIV (September 1971), 36-49.

\_\_\_\_\_. "Expanded R&D for the Electric Utilities." Paper presented at the Edison Electric Institute, 41st Annual Convention, Dallas, Texas, April 2-4, 1973.

Summers, Claude M. "The Conversion of Energy," *Scientific American*, CCXXIV (September 1971), 148-160.

Takahashi, Yasundo, Michael J. Rabins, and David M. Auslander. *Control and Dynamic Systems*. Reading, Massachusetts: Addison-Wesley Publishing Co., 1970.

- U. S. Department of Commerce, Bureau of the Census. *Annual Survey of Manufacturers: 1970; Fuels and Electric Energy Used by Major Industry Groups*. M70(AS)-4. Washington, D. C.: Government Printing Office, 1972.
- \_\_\_\_\_. *Statistical Abstract of the United States: 1972*. 93d ed. Washington, D. C.: Government Printing Office, 1972.
- U. S. Department of Labor, Bureau of Labor Statistics. *Outlook for Computer Process Control: Manpower Implications in Process Industries*. Bulletin 1658. Washington, D. C.: Government Printing Office, 1970.
- "U. S. Utilities Boost Budgets by \$2.7-Billion for 1973," *Electrical World*, March 15, 1973, pp. 38-42.
- Van Vlack, L. H. *Elements of Materials Science*. 2d ed. Palo Alto, California: Addison-Wesley Publishing Co., 1964.
- Welles, John G., et al. *The Commercial Application of Missile/Space Technology*. Denver, Colorado: University of Denver Research Institute, September 1963.
- Wessel, E. T., and W. G. Clark, Jr. "Fracture Prevention Procedures for Heavy Section Components." Paper presented at the American Society of Metals Conference on "Fracture Control: Theory and Application," Philadelphia, Pennsylvania, January 26-28, 1970.
- White, David C. "Energy, the Economy, and the Environment," *Technology Review*, LXXIV (October/November 1971), 18-31.
- White, John S. Control Theory Group, NASA Ames Research Center, Moffett Field, California. Telephone interview on January 5, 1973.
- Willis, William. Assistant to the Director, Division of Construction, Tennessee Valley Authority, Knoxville, Tennessee. Telephone interview on July 26, 1972.
- Woodruff, Phil. Project Manager, TRW Systems, TRW, Incorporated, NASA Manned Spacecraft Center, Houston, Texas. Telephone interview on January 5, 1973.
- Young, James F. "Challenges to the Manufacturer," in *Proceedings of the American Power Conference*. Vol. 26. Chicago: Illinois Institute of Technology, Technology Center, 1964.
- Yukawa, S. "Evolution of Fracture Prevention Criteria for Steam Turbine and Generator Rotors." Paper presented at the 1969 annual meeting of the American Society of Mechanical Engineers, Fracture Control Plans Session, November 17, 1969.